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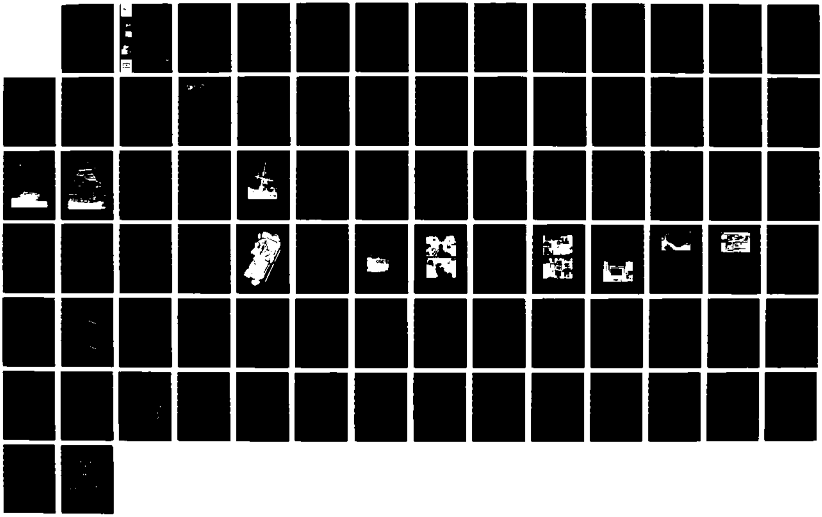

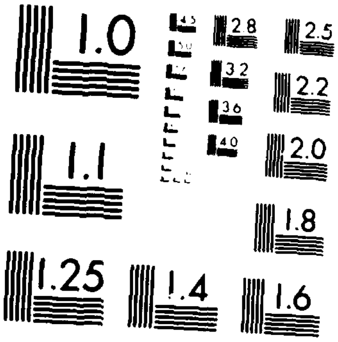

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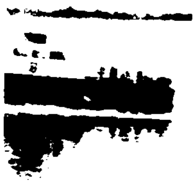

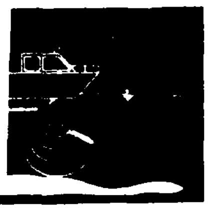

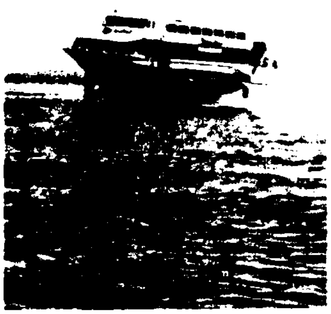

HYDRAULICS LABORATORY

TECHNICAL REPORT HL-87-10

# EVALUATION OF VERTICAL MOTION SENSORS FOR POTENTIAL APPLICATION TO HEAVE CORRECTION IN CORPS HYDROGRAPHIC SURVEYS

by

DTIC FILE COPY


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This report describes techniques and equipment that can help surveyors obtain the best practical vertical reference for hydrographic surveys in the face of adverse tide, river stage, and wave conditions. US Army Engineer Waterways Experiment Station efforts involved evaluating a heave compensation system (HIPPY 120) selected by the National Oceanographic and Atmospheric Administration and exploring the possibility of using Doppler equipment for measuring vertical boat motion.

Some specific measurement techniques for monitoring vertical references for hydrographic surveys under given field conditions are addressed. Depth transducer draft, boat flotation plane, and shore references are discussed in Part I. Dynamic vertical motions of the boat hull are discussed in Part II. Vertical displacement measurement equipment using automatic electrooptical tracking systems, video-type optical tracking systems,


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laser leveling systems, and satellites is assessed and found to have potential for future consideration and application in improving survey accuracy.

Evaluation of a heave compensation unit based on a pendulum-stabilized accelerometer platform (HIPPY 120) was attempted on a survey boat in the US Army Engineer District, Philadelphia. Protracted difficulties with the system prevented a quantitative evaluation. After the first installation was found to be unsuccessful, the HIPPY 120 was transferred to a survey boat in the US Army Engineer District, New York. The results, however, were much the same as in the first installation. These results lead to the conclusion that for this system to be successfully used during actual survey operations, there must be a higher-than-average level of technical skill among the personnel on the survey boat.

An effort was made to validate Doppler equipment for use in heave compensation. Measurements were made at dockside and also during actual survey operations using a modified Doppler navigator. The tests conducted indicated that the measuring principle was sound but also that much additional development was needed. Funding constraints and the entry on the market of a commercial Doppler heave compensation unit resulted in the decision to discontinue development of the Government-sponsored Doppler heave compensation unit.

## PREFACE

This study was sponsored by the Office, Chief of Engineers (OCE), US Army. The Technical Monitor for the study was Mr. M. K. Miles of OCE under the general supervision of Mr. William McCormick, Chief of the Engineering Division, Directorate of Engineering and Construction, OCE. The study presented in this report was performed at different intervals from 1979 to 1983 by the US Army Engineer Waterways Experiment Station (WES).

The study was conducted under the supervision of Messrs. H. B. Simmons and F. A. Herrmann, Jr., former and present Chiefs of the Hydraulics Division, respectively; and Messrs. E. B. Pickett and M. B. Boyd, former and present Chiefs of the Hydraulic Analysis Division, respectively. Messrs. E. D. Hart, Chief of the Prototype Evaluation Branch, and G. C. Downing, Chief of the Special Services Branch, Instrumentation Services Division, were the Project Coordinators for WES. This report was prepared by Mr. Downing with the assistance of Mr. T. L. Fagerburg, under the supervision of Mr. Hart, and edited by Mrs. Beth F. Burris and Mrs. Marsha C. Gay, Information Technology Laboratory.

Acknowledgement is made to the individuals of the US Army Engineer Districts, Philadelphia, New York, and Portland, who actively participated in this investigation.

COL Dwayne G. Lee, CE, is the Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

| Multiply | By | To Obtain |
| --- | --- | --- |
| degrees (angle) | 0.01745329 | radians |
| feet | 0.3048 | metres |
| inches | 2.54 | centimetres |
| miles (US statute) | 1.609347 | kilometres |
| pounds (mass) | 0.4535924 | kilograms |

# EVALUATION OF VERTICAL MOTION SENSORS FOR POTENTIAL APPLICATION TO HEAVE CORRECTION IN CORPS HYDROGRAPHIC SURVEYS

## PART I: INTRODUCTION

### Background

1. Hydrographic surveying in the US Army Corps of Engineers is big in volume, geographic extent, and cost. Hydrographic survey crews provide invaluable information on the underwater world where the Corps spends a high percentage of its civil works efforts in maintaining and improving this Nation's waterways. Surveying is an essential part of Corps engineering, construction, and maintenance projects, whether in dredging, flood control, hydroelectric projects, navigation locks, or hydraulic research. In all of these projects, accuracy of surveying affects directly the cost of a project and safety of users. From the shear volume of the business, it is obvious that small errors in the surveys can cause large dollar errors in payment for dredging work.

2. As an example of the cost effect of survey accuracy, consider a channel cut 5,000 ft* long and 1,000 ft wide. At a contract price of $0.50 per cubic yard, a depth error bias of 0.1 ft can result in an overpayment or underpayment of approximately $10,000. As another example, consider the huge cost of Corps dredging and what 1 percent of this cost would be. Having only a 1 percent error in the vertical dimension is probably optimistic, considering the techniques currently accepted. Safety of navigation in Corps-maintained shipping channels is strongly related to survey accuracy. Mariners depend on charts that are only as accurate as the survey data on which they are based. A single grounding can have a multimillion dollar negative impact on the Corps. It is therefore obvious that there is a need for the most accurate hydrographic surveys possible within technical state-of-the-art constraints and practical cost constraints. In recognition of this need, the Corps has for many years supported research and development directed toward improving survey technology.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

## Scope of Study

3. This study was initiated as a state-of-the-art search for techniques and equipment that potentially could be used in Corps survey boats for the abatement of heave effects. This study did not address horizontal positioning error factors. An early finding was that the National Oceanic and Atmospheric Administration/National Ocean Service (NOAA/NOS) had a heave research effort underway and their program already had progressed to the stage of prototype testing. As the goal of the NOAA/NOS heave research was very similar to that of the Corps, it was decided that the US Army Engineer Waterways Experiment Station (WES) should review the NOAA/NOS effort to avoid duplication. WES effort was therefore shifted partially to monitoring the NOAA/NOS heave research program. After the NOAA/NOS basic research was completed and a tentative solution had been selected, it was considered appropriate for WES to begin active development work. WES decided to pursue two avenues of evaluation and development that were Corps-specific:

a. Evaluate the heave system selected by NOAA/NOS in a large Corps survey boat equipped with a computer-based survey system. The heave sensor selected by NOAA/NOS was one manufactured by Datawell and designated the HIPPY 120* (described in Part III).

b. Explore the possibility of using Doppler equipment for measuring vertical motion of survey boats. This was considered a potentially useful heave measurement technique, but it had not been studied in the earlier NOAA/NOS research and development effort.

This study was limited by funding and time constraints to the evaluation of techniques that were already developed to some extent. This report summarizes some of the recent Corps hydrographic survey work aimed at improving the accuracy of depth measurement by improving the vertical reference and provides other information which will benefit field support elements. Refining the dynamic vertical reference will receive the primary emphasis in this report, but the closely related factors of tide, river stage, and transducer draft will also be discussed.

## Survey Conditions Most Needing Improved Vertical Reference

4. The precision that should be sought in a given survey will vary with the type of survey and the intended use of the data. Where Government

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* HIPPY is a registered trademark of Datawell Corporation.

expenditures are determined by quantity computations, techniques that ensure the best practical repeatability should be used. A suggested goal for dredge quantity surveying is to use techniques that have the precision to give an overall repeatability of 0.2 ft. For surveillance surveys, the use of techniques that have a precision of 0.5 ft is suggested. The difficulty in achieving the desired level of precision, repeatability, and accuracy will be strongly influenced by the natural conditions at a survey site. Some examples of field conditions that warrant special effort to achieve suitable vertical accuracy are the following:

- a. Offshore channels that must be dredged.
- b. Estuary inlets with swift tidal currents.
- c. Bays where incoming regular waves are reflected from the shoreline and form interference patterns (standing waves).
- d. Waterways with frequent large ship traffic, as large ships cause nonrepetitive surges.
- e. Areas near dikes or other subsurface structures (natural or manmade) as swift currents all cause short-term deviations from the geoid surface.
- f. Near shore where waves are highly asymmetrical.
- g. Where survey lines run approximately parallel to incoming wave fronts.
- h. When a predredge survey is made during spring tide conditions and the postdredge survey is made near neap tide.
- i. When searching for small discrete objects such as boulders or wrecks.

## Factors Affecting the Vertical Reference

5. Depth measurements are made with respect to the water surface supporting the survey boat at the time of a hydrographic survey. These time-dependent depth measurements should then be adjusted so that dynamic water-surface fluctuations are eliminated and the final depth data are correlated with an established nontime-dependent survey monument on land. Many factors affect the water-surface reference for hydrographic surveys. As measurement techniques improved, it is possible for more of the secondary factors to be taken into account. While this report primarily addresses boat heave corrections, it was thought appropriate to summarize in this section most of the other factors affecting the vertical water-surface reference. This approach

permits boat heave to be presented in the proper perspective, of being one of many factors that should be accounted for when planning a hydrographic survey. It also allows the importance of considering the rate of change of each of the contributing factors listed in the following paragraphs to be emphasized.

Instability of benchmarks

6. Land instability should not be neglected if a goal of 0.1 ft precision in the vertical datum is sought. For instance, land subsidence in the Lower Mississippi Valley can affect benchmark position as much as 0.2 ft per year referred to the National Geodetic Vertical Datum (NGVD). Land subsidence in this area is due to a combination of deltaic sediment consolidation, pumping from gas and oil wells, and downwarping, which is increased by the weight of delta sediments. Most sections of the country are more stable than this example of steady subsidence, but no section is completely immune. Some areas of California have large subsidence from oil well and groundwater pumping operations. Some areas of the country are rising rather than falling. Parts of the Great Lakes shore seem to be experiencing a postglacial uplift (Zilkoski and Young 1985, Feldscher 1975). Slowly changing vertical benchmarks do not affect the accuracy of dredge computations because the time difference between the surveys is too short for the land changes to be significant. Land subsidence or uplift becomes a problem when the survey data are used to establish navigation channel depth. Undetected subsidence of benchmarks can lead to unnecessary dredging and thus to unnecessary costs. Undetected uplift of benchmarks can lead to the development of navigation hazards. Surveyors should reassess the quality of benchmarks prior to surveys. The Global Positioning System (GPS) satellite system makes it possible to check the stability of all areas of the country at a far more reasonable cost than was previously possible.

7. Other factors can affect the stability of benchmarks. In contrast to the slowly changing character of land subsidence and uplift, the abrupt changes that occur with earthquakes must be considered. California and the Central Mississippi Valley have the highest risk for major earthquakes, but the Northeast Coast is not immune. Surveyors should reassess benchmark stability whenever a significant earthquake occurs in a survey area. Here again, in the future, the GPS system will make the checking of benchmarks much faster and cheaper than with conventional techniques. Frost heave is a problem for cold region surveyors. Techniques for building frost heave-resistant

benchmarks have been developed that can help in some conditions (Gatto 1985). A problem that is anticipated with benchmarks is the conversion from the National Geodetic Vertical Datum of 1929 (NGVD 29) to the North American Vertical Datum of 1988 (NAVD 88) (Zilkoski and Young 1985). This conversion will require particular diligence on the part of those who handle the data processing aspect of surveying.

Ocean level fluctuations

8. Tidal fluctuations due to earth-moon-sun interactions are predictable on a large-scale basis, but many local and transient factors can cause the actual water level at a given time and place to be quite different from the theoretical value. Thus, theoretical tide predictions are normally not adequate for survey tide compensation. Measurement of actual water-surface level as a time-varying function in the close vicinity of the channel being surveyed is necessary for adequate depth adjustment (Figure 1). The

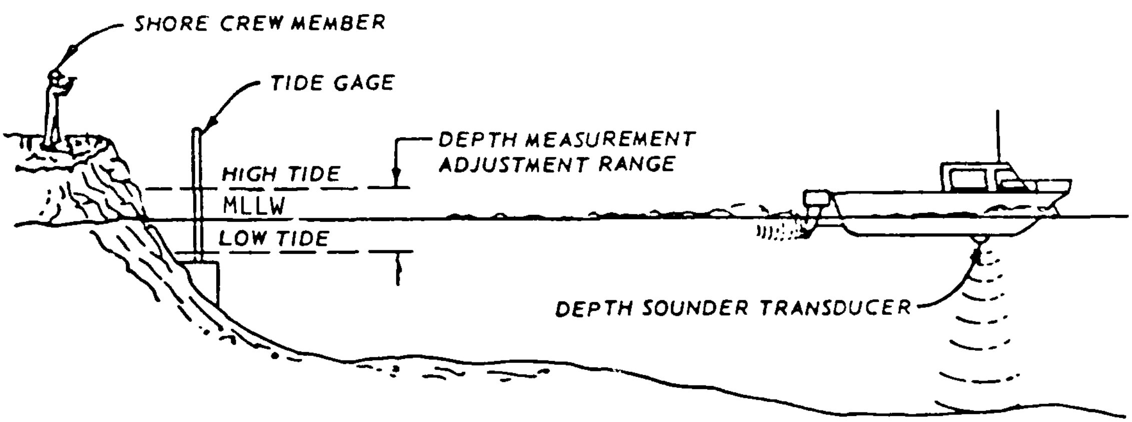
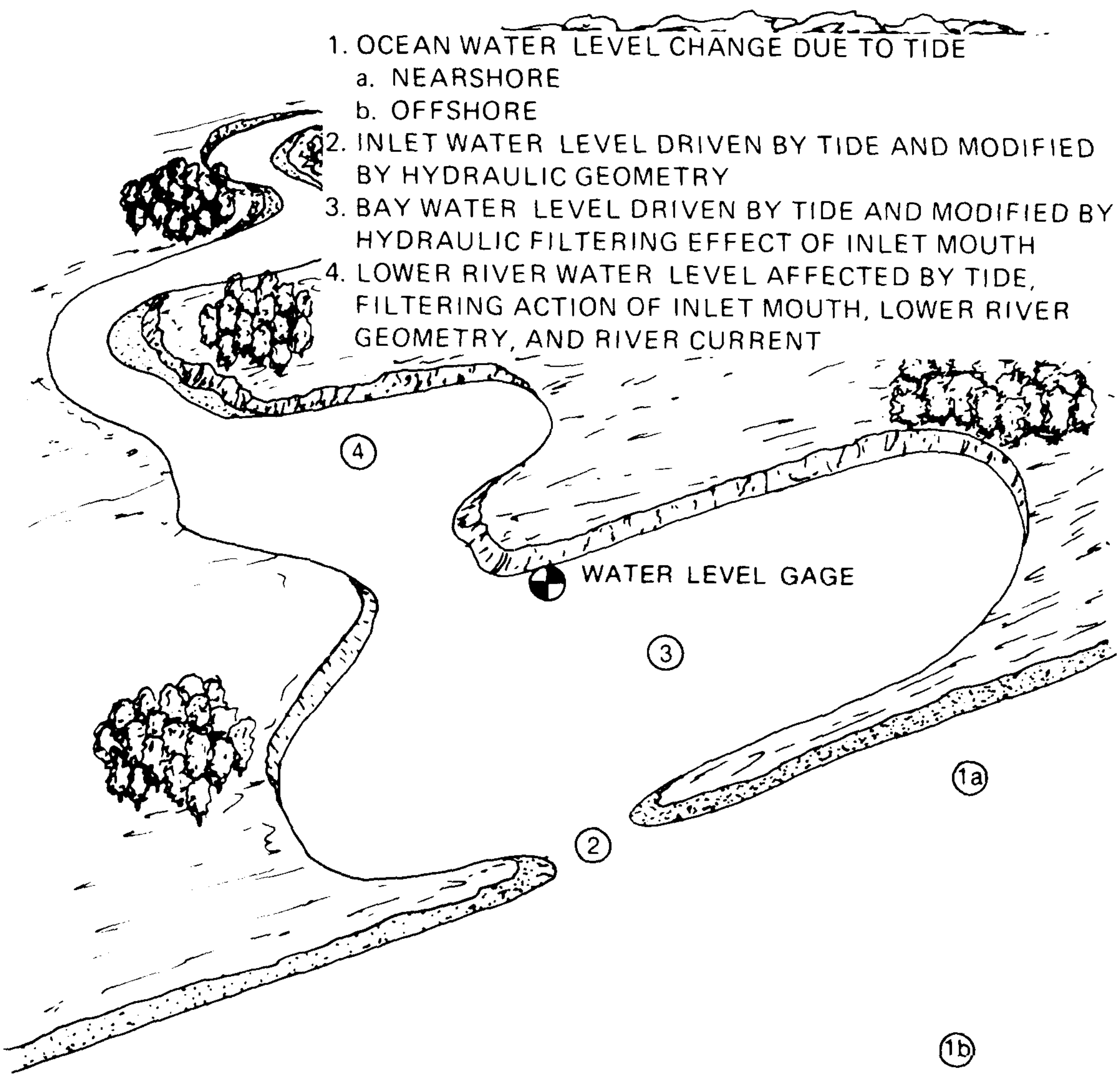
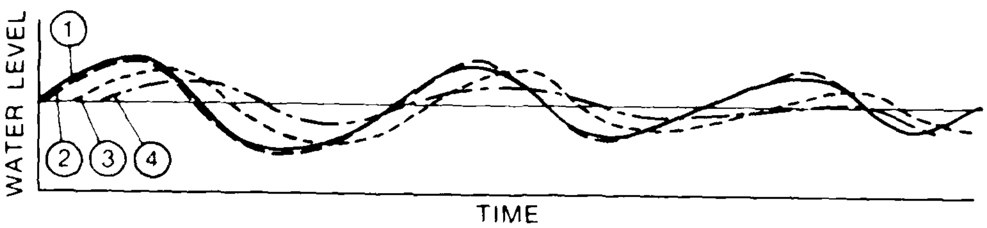



Figure 1. Tidal correction for depth measurement

importance of the location of the water level measurement must be emphasized. Hydraulic effects caused by the interaction of tidal currents and waterway geometry will alter the amplitude and phase of local tide levels (Figure 2). Wind, seiches, atmospheric pressure, and ocean currents can add to the complexity. Figure 2a illustrates some of these effects. The offshore tide (area 1b) can be significantly different from the nearshore tide (area 1a) due to the interaction of currents and land projections. An estuary inlet water level (2) can differ significantly from both the nearshore tide level (1a) and the bay level (3) except, possibly, near slack tide time when there is very little tidal current. Tidal fluctuations in a bay (3) will lag the shore tide and usually have a lower amplitude as illustrated in Figure 2b. Water-surface




a. Effects of waterway geometry on tide levels




b. Time-history of tide levels at various locations in the waterway

Figure 2. Hydraulic effects of waterway geometry

level within a bay can have deceptive fluctuations due to hydraulic resonances (seiches). Atmospheric pressure changes and ocean level surges can induce "sloshing" of the water in a bay or lake. These surge-induced water level oscillations will be superimposed on the "normal" or predictable tide. Farther inland in an estuary (location 4, Figure 2) the tidal effects are further complicated by river currents, discharge rate, and changing salinity. This review of the numerous factors affecting the dynamic vertical reference for hydrographic surveys should help to emphasize the importance of adequately measuring the water surface supporting a survey boat at the time a hydrographic survey is made. "Adequate" includes accurate water level amplitude, time of measurement, and location of measurement close enough to eliminate any significant difference between the water level measured and the water surface supporting the survey boat.

Tide measurement techniques

9. Tide measurement techniques have been developed that give surveyors the capability of greatly improving the accuracy of the location of the vertical reference (Bodnar 1982). Offshore tide gages (Howard 1979 and Batty 1982) have been installed by several Corps districts to provide an adequate offshore vertical reference for surveys in inlet channels. The offshore tide gage discussed in these references was constructed by building a platform at the desired gage site. The platform was built by embedding a large-diameter steel pipe in the offshore sediments. Once this stable onsite platform was completed, then simultaneous observations were made of tide at this location and at several onshore primary tide stations. The method of simultaneous comparisons was used to establish a mean low water datum at the offshore site. A minimum of 30 days' continuous observation is needed to establish a tertiary tide station such as this one, but longer observation periods can, of course, give more accurate results. The savings possible from improved vertical references can be measured in the millions. The Norfolk District documented $1.7 million in less than one year by improving the datums on five projects (Miles 1979).

Tide measuring equipment

10. Tide measurements within an estuary can be improved in several ways. For instance, if several tide gages are installed in a bay, the simultaneous observations from them can be used to determine if seiche effects are occurring during a hydrographic survey. The tide gages in such a multiple set

would not need as long an observation history as would be necessary when installing an absolute shore reference. Simultaneous measurements within one tidal cycle can provide enough information to determine if the whole bay surface is moving up and down at the same rate or if it is "sloshing" back and forth with opposite sides of the bay 180 deg out of phase. After vertical motion conditions within a bay are determined with simultaneous observations, it will then be possible to logically determine the minimum number of tide gages that will be needed throughout the survey time interval. Temporary gages can be installed quickly using currently available commercial equipment. Acoustic reflection water level gages (Spies 1982) require the installation of only a small tube in the water, compared with the large-diameter pipe required for a float-type water level gage. The installation of the small acoustic gages is thus considerably quicker and less expensive than that of float-type gages, with a corresponding decrease in installation costs. Acoustic-type water level gages normally would be combined with a radio telemetry unit so that real-time tide data can be sent to the survey boat. Acoustic water level gages are not affected by the salinity of the water at the measurement site since this type equipment works by reflection from the water surface, not buoyancy or density of the water.

11. Another type of instrument that can be used to measure tide is a pressure transducer and associated components. Pressure-type water level gages have the considerable advantage that they can be installed as completely submerged tide stations (DeWolfe 1975). This characteristic permits them to be installed on the side of a channel to be dredged and thus much closer to the survey area than is possible with tide gages that must be installed on the shore. Pressure-type submersible water level systems can be designed to include telemetry or internal recorders or both. Submerged tide gages with only an internal recorder can provide only after-the-fact information whereas tide gages with telemetry can provide real-time information about water level. The use of pressure-type tide gages very close to the survey and dredge sites provides surveyors with a method of determining if shore-sited tide gages are adequate for a given channel or survey area or if the water level must be measured closer to the survey or dredge site. Because installing, maintaining, and communicating with onsite water level gages can be expected to be more expensive than using shore-based tide gages, the latter approach should be used when direct measurements prove it feasible in a given area. Measurements

of a few tidal cycles should prove whether phase and amplitude of the tide at a submerged gage site are sufficiently close to the measurements at a shore site that the latter can be used. If direct measurements prove that the shore site does not adequately represent tide level changes in the area to be surveyed, then the surveyor should take the additional time and expense to establish close-in submerged tide stations. By using underwater moorings and acoustic homing signals, it is possible to establish relatively long-term subsurface stations (DeWolfe 1975, Oswald and Wolaver 1985).

12. Pressure-type water level gages require certain care and compensation not necessary with gages that measure water surface directly as do acoustic reflection and float-type gages. Pressure gages respond to the total applied pressure which includes both the water column and the atmospheric pressure. Submerged tide gages require an additional simultaneous measurement of atmospheric pressure if the best possible water level measurement is to be computed. It is possible to make pressure transducers respond only to applied water pressure if a gage-type transducer is used and if a reference pressure port to atmospheric pressure is practical to install. An atmospheric pressure port is practical only at shore tide stations, and this is not where the big advantages of pressure-type tide gages are most evident. Atmospheric pressure compensation is thus a probable need in most pressure-type tide gage installations.

Salinity effects

13. Pressure-type water level gages are sensitive to salinity changes because a change in salinity causes a corresponding change in density. Pressure at a submerged gage site is proportional to both the height of the water column and the density of the water. In Figure 3 a simplified sketch illustrates how tide gages in estuaries may be in locations that alternate between brackish and ocean salinity. High tide and low river discharge can shift the saltwater/freshwater interface to an area closer to the mouth. Water level gages based on pressure measurement (such as bubbler gages and pressure transducers) will give different readings for the same absolute surface level if installed in an area with large salinity changes and a large range between high tide and low tide. The lower Columbia River is an example of such a situation. The difference in pressure between a 10-ft freshwater column and a 10-ft saltwater column can be as much as 0.25 ft (Oswald and Wolaver 1985). In estuaries with large tide ranges, the surveyor should check the salinity

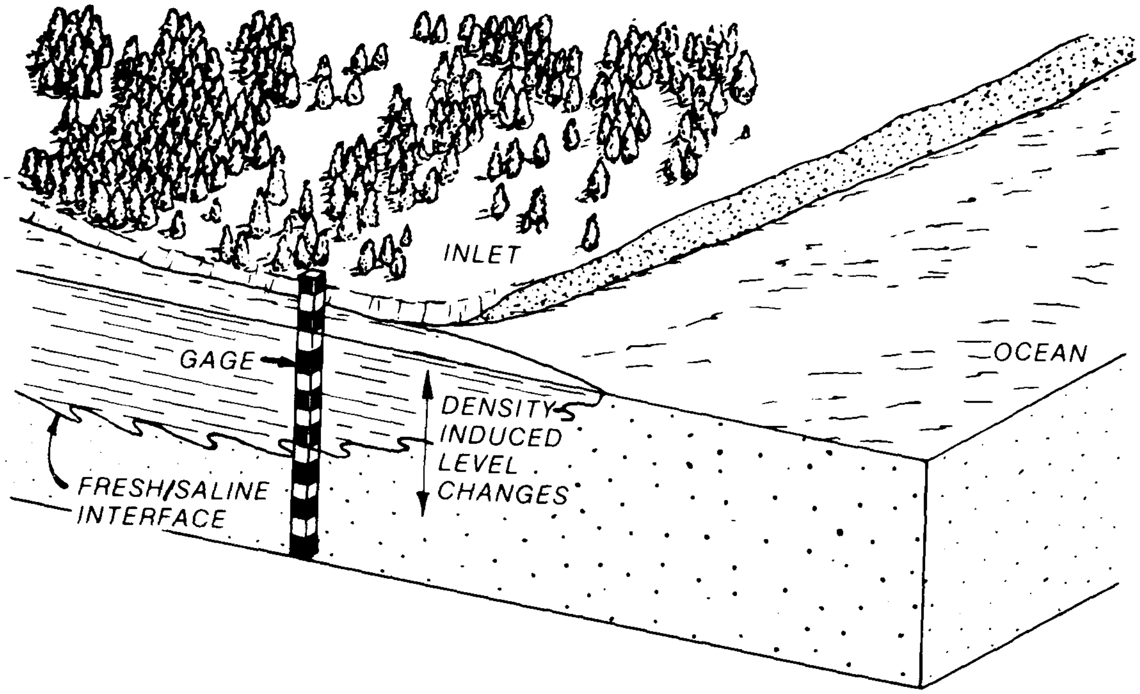



Figure 3. Cross section of inlet geometry showing salinity-induced changes in tide gage reading

changes in the vicinity of the tide gages and make compensations if necessary. In estuaries where the tide range is small (as is typically the case in the Gulf of Mexico) then the error in water level measurement due to salinity changes is probably negligible for hydrographic survey work. For establishment of a tertiary and secondary tide station, salinity changes should be considered even in areas with a small tide range.

14. Salinity changes in an estuary also affect the draft of displacement hull vessels. This change in draft is probably negligible in survey boat vertical reference accuracy and performance. It may be significant, however, for large cargo ships running close to the maximum draft limit during low tide. A given depth of salt water will cause a ship to float higher above the bottom than will the same depth of fresh water. During tide and riverflow conditions that cause an estuary channel to be fresher than usual, for a given water level, then, ships could run aground that would normally pass. Thus, knowledge of salinity changes in some estuaries may be a necessary supplement to depth measurements if complete assurance of navigation clearance is to be achieved.

## River stage fluctuations

15. River stage corrections to depth chart readings are inland waterway equivalents to tidal corrections. The rate of change of river stage is normally much slower than rate of change of tidal water level. Time correlation between river stage measurement and survey depth measurement is thus not as critical as the time correlation of tide gages for surveys in tidal zones. River stage readings can be spaced to convenient points in time so long as the stage at the time of the survey can be interpolated with confidence to 0.1 ft.

16. Waterway geometry and river currents interact to produce effects that are sometimes overlooked in adjusting inland waterway depth measurements to a "standard" reference. Figure 4 illustrates one example of subsurface geometry that induces a localized water-surface level change. Surveys near dikes or natural rock ledges will be affected by local distortion of the water surface. The magnitude of the effect will vary with river current and stage.

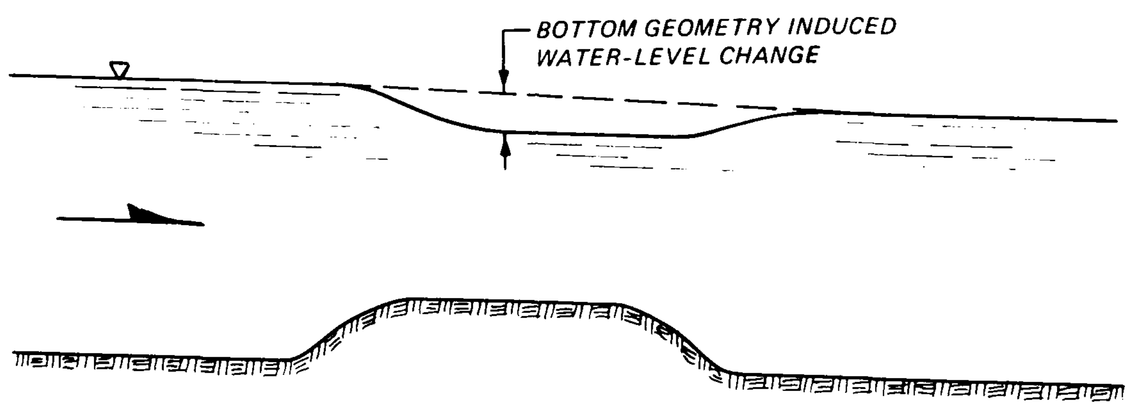



Figure 4. Localized effect of subsurface geometry on water levels in rivers

17. Centrifugal effects in sinuous rivers, or Coriolis forces in estuaries, cause another deviation from a hypothetical level water surface. Figure 5 illustrates the buildup of surface level on the outside bank of a bend in the river and a depression of the surface level on the inside bank. These localized surface effects will influence both the depth measurements and stage measurements taken in the river bends when current is swift. The preferred location for measuring river stage is along a section with little curvature and minor change in cross section.

## Survey vessel draft

18. Survey vessel draft is not a static parameter. Transducers emit an acoustic signal for depth measurement and are usually mounted in the bottom of

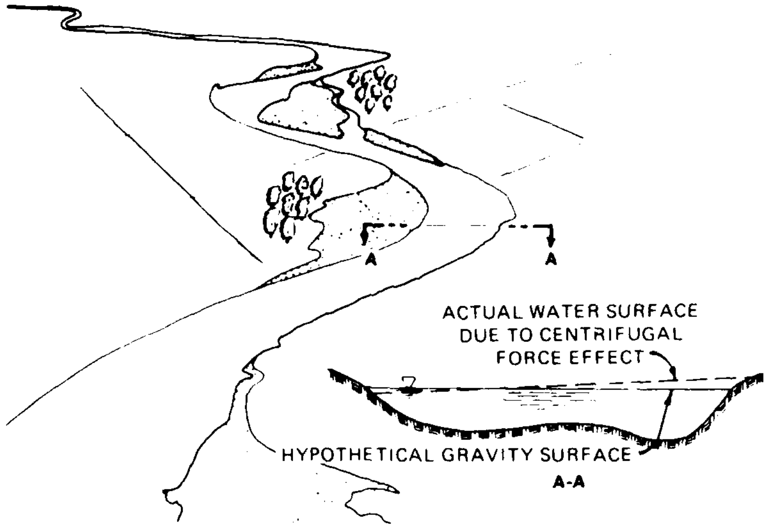



Figure 5. Centrifugal force effect on water level in rivers

the hull of the survey boat. The acoustic signal travels from transducer to waterway bottom and back to transducer. By proper calibration of the relation between signal transit time and distance traveled, the depth measuring system determines distances between the transducer and waterway bottom. These distance measurements must be corrected for the difference between the reference surface and the depth of the transducer face to determine bottom depth. This correction is typically referred to as draft correction (Figure 6).

19. Draft is also frequently based on a static measurement of transducer position with respect to the water surface. In actual survey operation,

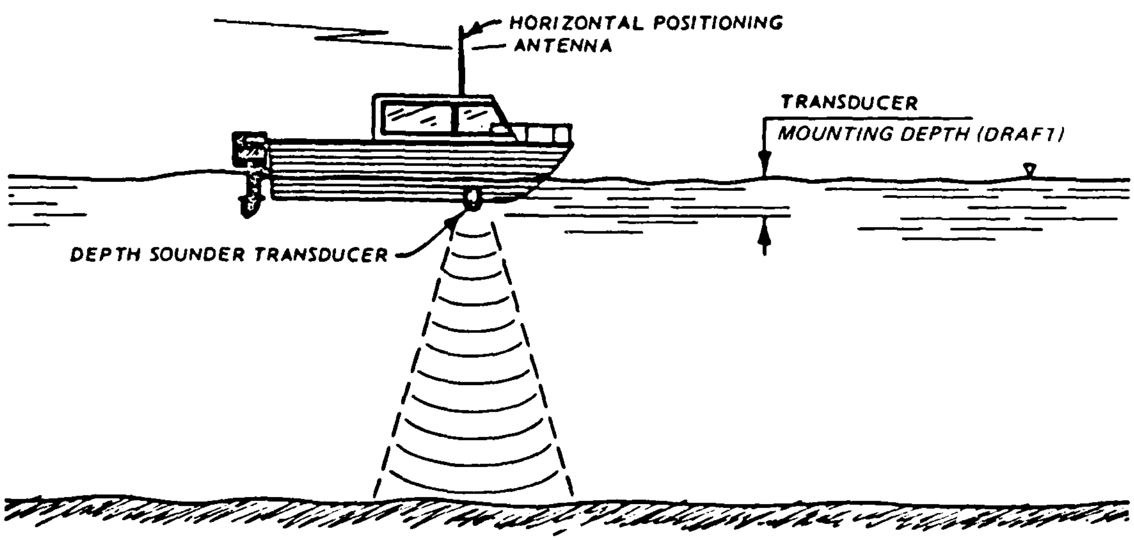



Figure 6. Draft correction for depth measurement

the boat is supported by both buoyant and dynamic effects of the water, and the transducer location changes significantly with respect to the water-surface level when boat speed changes from zero to operational speed. Draft corrections thus should be based on the position of the depth transducer with respect to the water surface when the survey boat is at operational speed. Transducer depth can be checked by piloting the survey boat over a submerged plate placed at a known location and depth. During this calibration run, the survey boat must be operated at the same speed as will be used in subsequent surveys. If a survey boat is to be used at several operational speeds, then several draft calibration runs should be made to determine different draft corrections for different speeds. This calibration method can be used both with fabricated platforms and over natural waterway bottoms, if flat, level bottoms exist in the area to be surveyed. If fabricated platforms are being considered by a District, it must be kept in mind that the platform must be large enough to get two or three depth signal returns while the boat is passing over the platform. Unless the depth recorder to be used can transmit and receive signals at a rate of 10 pulses per second, this approach will require unreasonably large platforms. Accurate guidance is also necessary, for the boat must pass directly over the platform for the measurement to be accurate.

20. Another dynamic draft calibration technique that also can be used involves transits or level. A vertical staff is placed on the survey boat and a transit station is placed on shore. The vertical staff on the boat must be painted with highly visible height marks. A static check of boat draft is then made and correlated with a static check of vertical staff position with respect to the shore sighting station. The boat is then run past the shore sighting station at operational speed and another sighting on the vertical staff is made. The difference between the static and moving staff readings can be used to correct for moving boat draft changes. For this optical sighting technique to be accurate, it is necessary that the vertical staff be placed as close as possible directly over the depth-measuring transducer. Otherwise the vertical staff and depth transducer will not have the same change in static-to-dynamic position.

Wave action

21. Wave action is a short-period dynamic fluctuation in a waterway surface that causes several undesirable effects in depth measurement. Vertical motion (heave) of the survey boat has a direct and proportional effect on

the depth measurement. If a wave crest lifts a survey boat 2 ft above the "average" water surface, the depth measurement at that point will be 2 ft deeper than the average depth (Figure 7). A wave trough will similarly shift the dynamic depth measurement to a shallower reading than the average depth. This is considered to be the primary effect of wave action. The average boat speed is also changed as the boat rises to and falls from the crest of each wave. The draft and squat of the boat hull will change between the wave crest and trough. This is considered to be the secondary effect of wave action. A short-period change in transducer draft can be determined with the heave measuring techniques discussed in subsequent chapters.

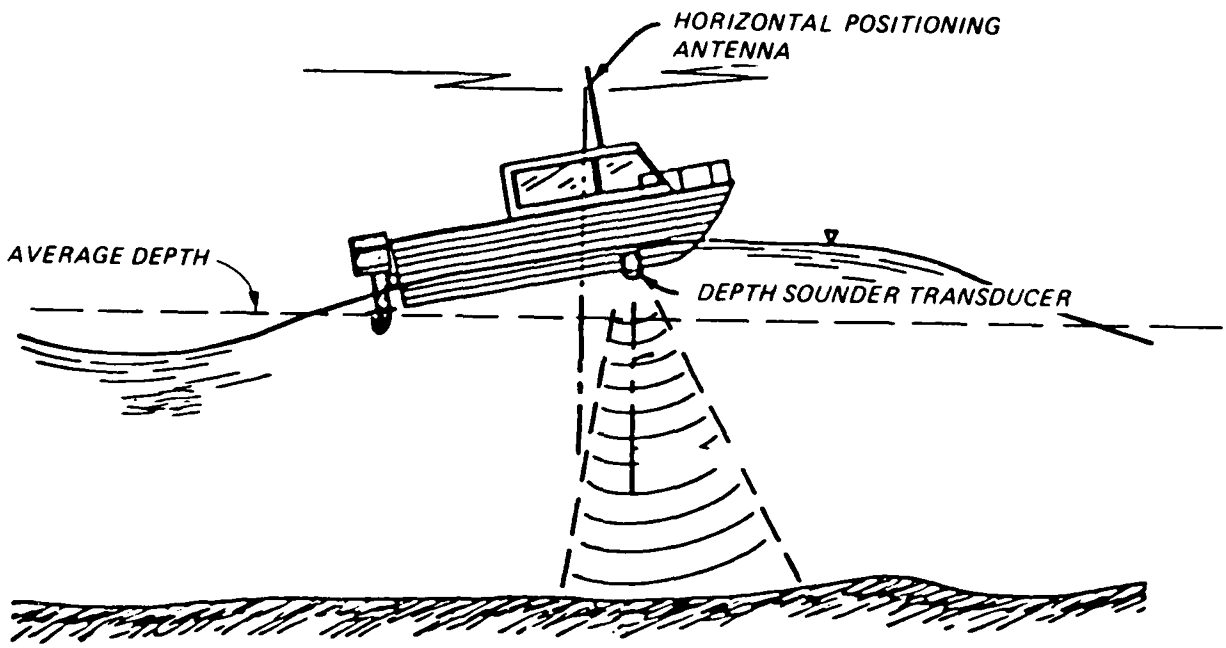
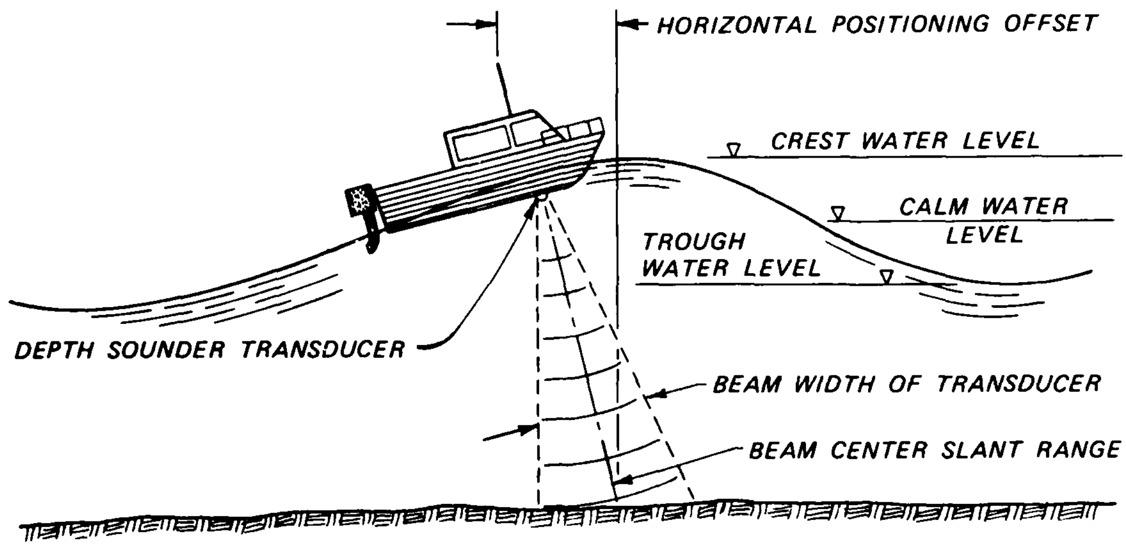


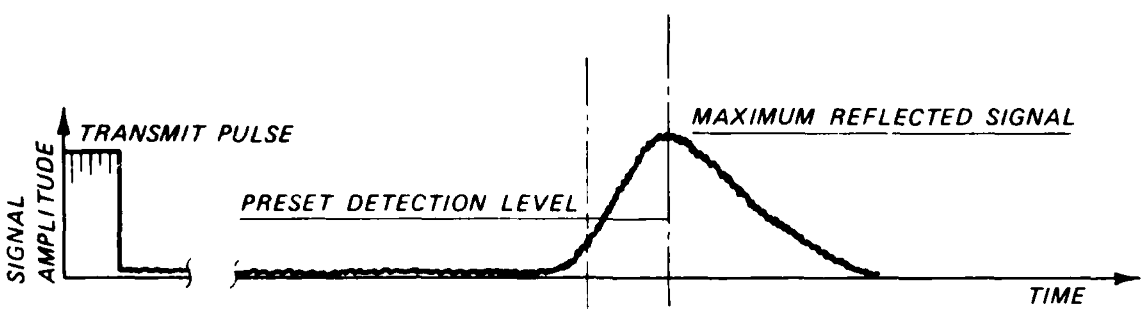

Figure 7. Depth measurement with dynamic water-surface reference

Pitch and roll

22. Pitch and roll induce changes in depth readings that are nonlinear and system-dependent. When boat motion causes the depth transducer to be pointed in a direction other than vertical, the principal bottom reflection will come from an area of the bottom that is not directly beneath the boat. The slant range to the bottom area where the transducer beam is pointing will be greater than the vertical distance from transducer to bottom (assuming a flat bottom) (Figure 8a). This slant range to the bottom increases as a cosine function. The cosine function changes slowly for angles less than




a. Pitch effect on acoustic beam pointing



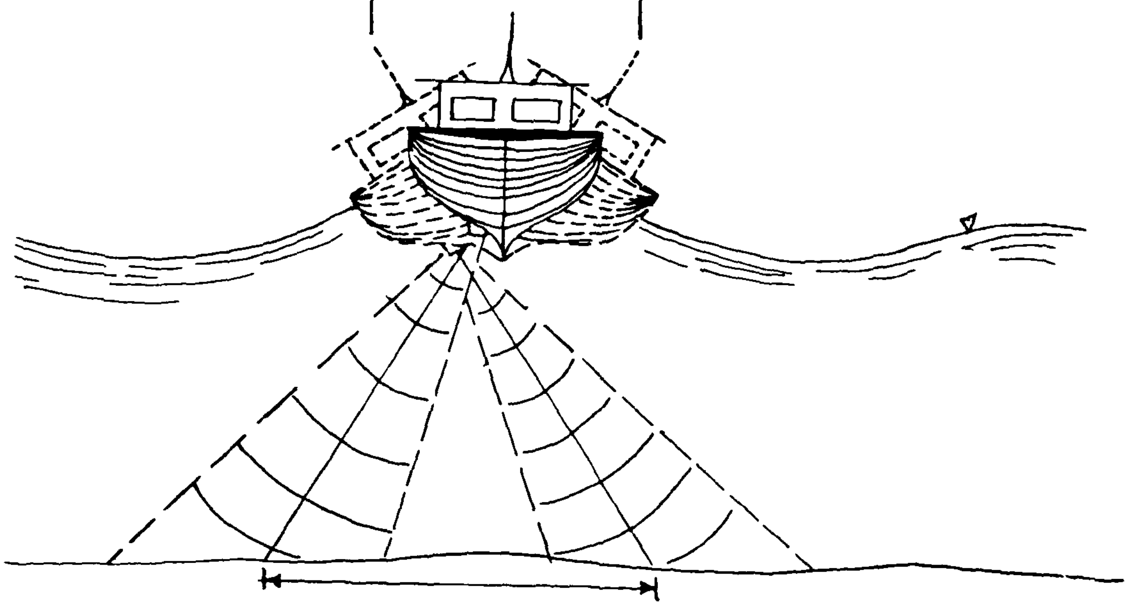

b. Time-history of acoustic signal

Figure 8. Effect of pitch and roll on depth readings

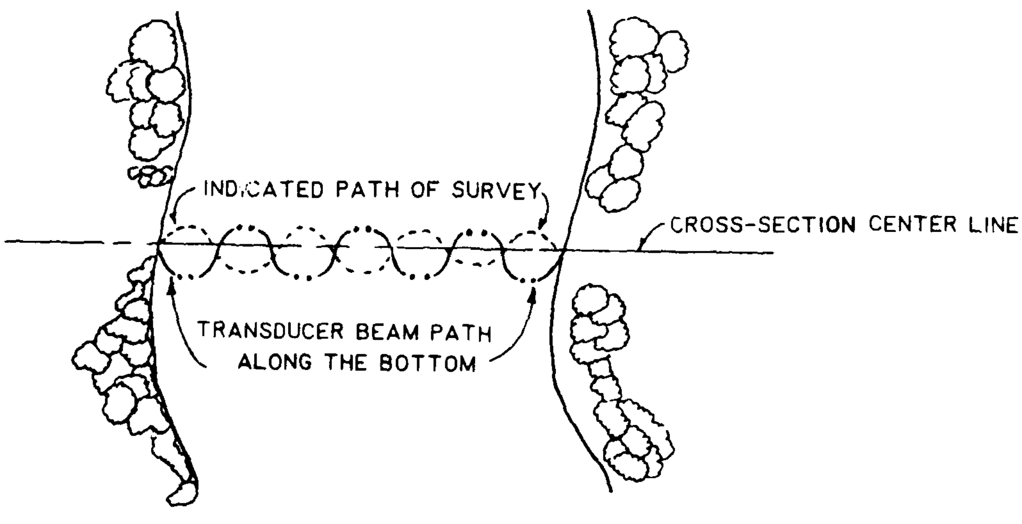
16 deg. The slant range change from the vertical in 32 ft of water is shown in the following tabulation. Thus, for minor pitch and roll there will be little slant range effect.

| Degrees from Vertical | Slant Range, ft |
|---|---|
| 0 | 32.0 |
| ±1 | 32.0 |
| ±2 | 32.0 |
| ±4 | 32.1 |
| ±8 | 32.3 |
| ±16 | 33.3 |

23. Depth measurement during pitch or roll is not a direct function of slant range, for the reading depends also on the transducer beam width, the type of depth detection circuitry, and the bottom acoustic reflectivity. Depth sounders determine depth by measuring the transit time of an acoustic pulse traveling from transducer to bottom and return. Measurement of transit time is based on (a) first return of reflected pulse above a preset level and (b) maximum return of reflected pulse. Depth sounders based on detection of the first return (or leading edge) will give a reading from an area on the bottom that is between the vertical distance and slant range (Figure 8b). The exact reading will depend on the preset detection level and the reflectivity and smoothness of the bottom. If a depth transducer is not slanted from vertical at an angle greater than its beam width, the reflection time detected will probably be very close to that for the true vertical distance. The shortest acoustic path from transducer to bottom in this case is the vertical line. The first return of the reflected acoustic pulse will thus also be along the vertical line. For a transducer tilted more than its beam width, the first detectable portion of the reflected pulse will be from an area other than vertical. Pitch and roll introduce an indirect error in horizontal positioning of the depth measurement (Figure 9) as a result of the slant range to the bottom. Tilt of the horizontal positioning system antenna causes a change in measured boat position. Tilt of the depth transducer beam causes a change in the point on the bottom where the depth is measured. The total horizontal offset error is the sum of the antenna shift and the depth transducer beam shift (Figure 9a). The net effect is equivalent to a boat operator weaving back and forth across a section line (Figure 9b). A survey section line originally run through waves thus cannot be accurately rerun even if the survey boat is equipped with a heave compensation system.




a. Horizontal offset error between positioning antenna and depth transducer beam




b. Indicated survey path and actual transducer beam path resulting from pitch and roll of survey vessel

Figure 9. Effect of pitch and roll on horizontal positioning of depth measurement

### Bottom effect

24. The smoothness of the bottom introduces another factor in the depth detection area. A bottom surface that reflects evenly at all angles will return approximately the same energy per projected unit area, independent of the transducer tilt. This is typical of rough bottoms or those with numerous acoustic reflector points such as gravel. A smooth bottom, though, will reflect less energy per unit area as the incident acoustic beam angle shifts away from the vertical. This effect can cause loss of bottom signal in some instances. It has the sometimes helpful aspect of tending to shift the depth reading closer to the vertical rather than beam center when the transducer is not pointing straight down. A depth sounder, with a depth detection circuit designed to determine depth based on peak signal amplitude, will give depth reading closer to the transducer slant distance to the bottom (Figure 8). Use of peak amplitude as a criterion for bottom detection is one method of distinguishing real bottom reflection from "false" bottom reflection. Since this detection method does respond primarily to energy along the transducer beam axis, it will be more sensitive to pitch and roll than a detection circuit based on first return.

### Transducer beam width

25. Transducer beam width has an important effect on the accuracy and what is revealed in the depth record. Depth sounder manufacturers can provide transducers with beam widths ranging from a few degrees to 39 degrees; the optimum choice depends on customer application. Beam width and transducer size are inversely proportional at a given frequency. Transducer beam width is also inversely proportional to frequency at a given physical size. The net result is that most narrow beam depth sounder transducers are high frequency ($\geq$100 kHz) and most broad beam transducers are low frequency ($\leq$100 kHz). The use of narrow beam and broad beam designations for depth sounder transducers is not clearly defined in most trade literature, but a good example of usage is given in the Raytheon DSF 6000 Fathometer* operations manual. For this instrument a 100 kHz/7.5-deg transducer is referred to as a "narrow beam" transducer. A 24 kHz/27-deg transducer is referred to as a "broad beam" transducer (see Figure 10). A narrow beam transducer will have higher energy levels in

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* Raytheon DSF 6000 is a registered trademark of Raytheon Oceans Systems Company.

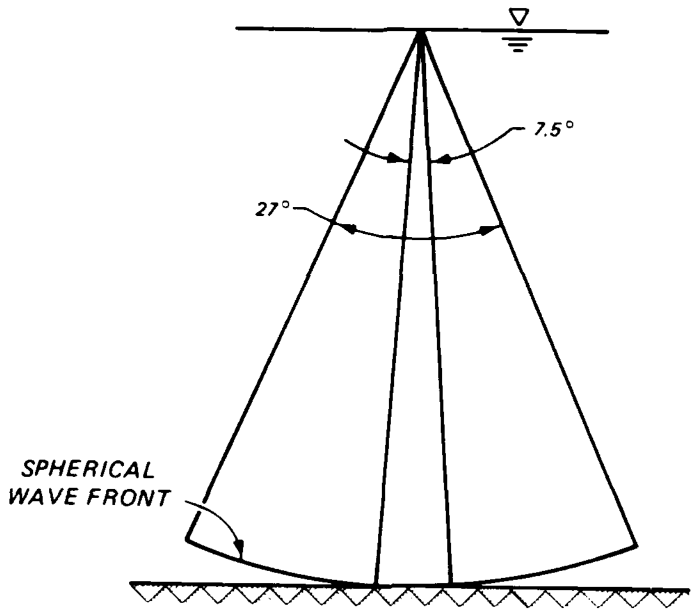



Figure 10. Illustration of high (narrow beam) and low (broad beam) frequency transducer fields of view

the directed beam and in the reflected signal than will a broad beam transducer at the same power level and frequency. The greatest spatial accuracy can be obtained from a narrow beam transducer. With this type of transducer, the reflected signal comes from a small area on the bottom. Extraneous reflections from side slopes and other irregularities are thereby kept to a minimum. Also, use of a narrow beam transducer will reduce the effects of acoustic noise arriving from directions other than the bottom.

## Alternate Approaches to the Problem of Heave-Induced Errors

26. Several basic alternative approaches have been considered for alleviating heave-induced errors in hydrographic survey depth measurements. An alternative approach does not mean simply a different way of measuring a useful parameter, but rather in a more general sense, how to eliminate or adequately alleviate an objectionable situation. In the following paragraphs some different approaches to the problem are summarized. Only one of these approaches, the measurement of vertical displacement, is considered in this study because of time and funding limitations. Figure 11 illustrates these alternate approach paths.

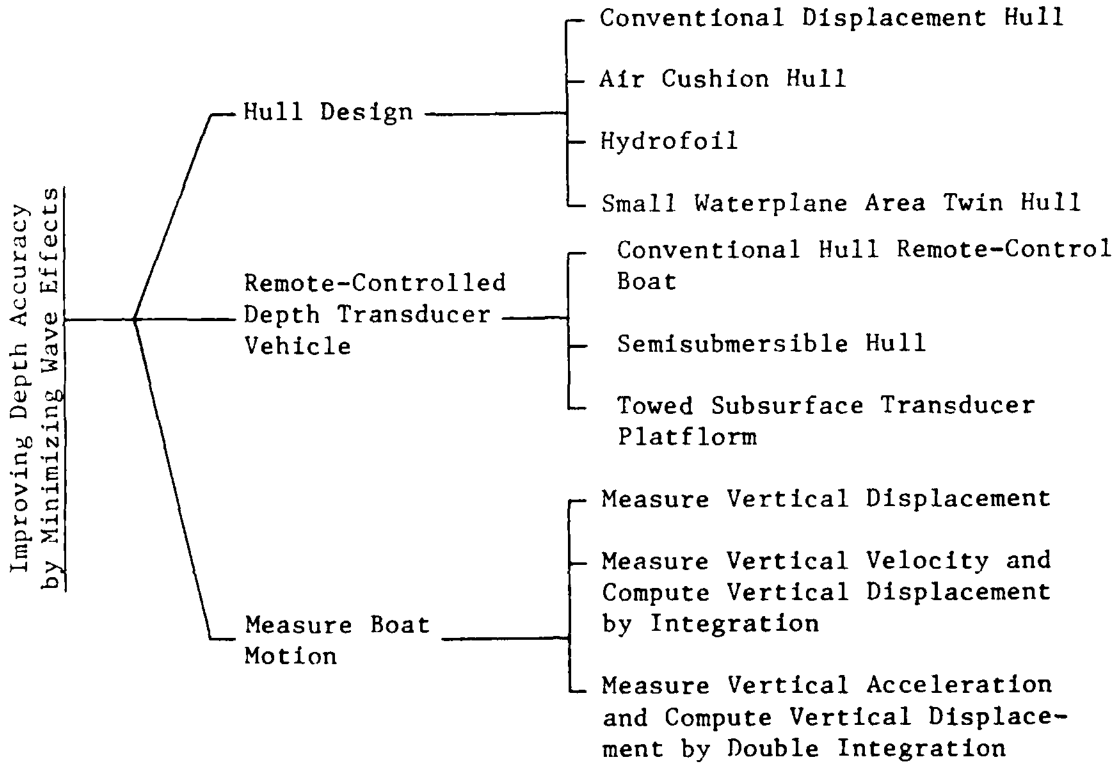
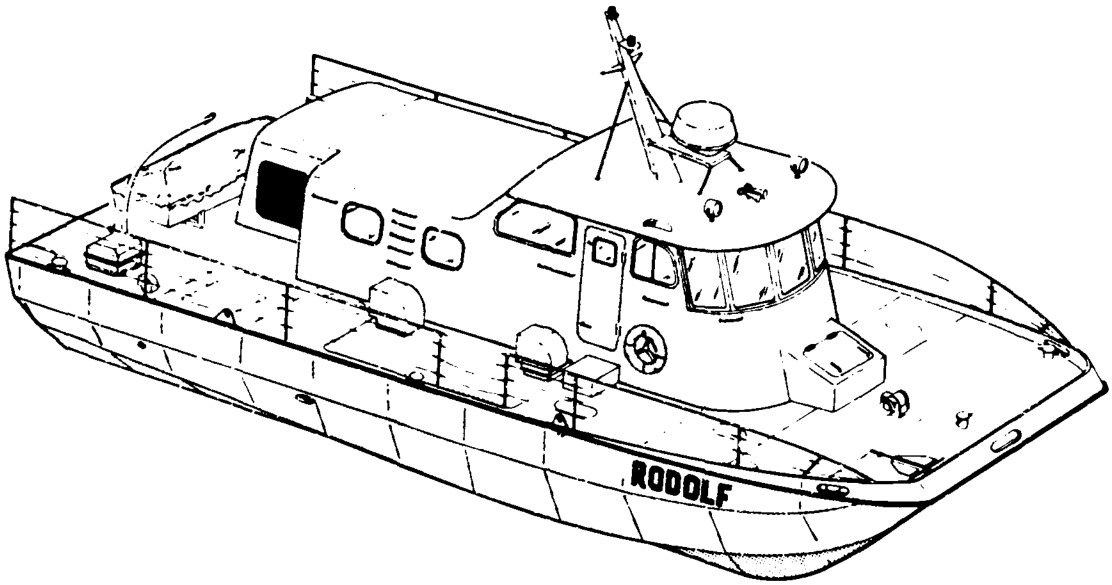


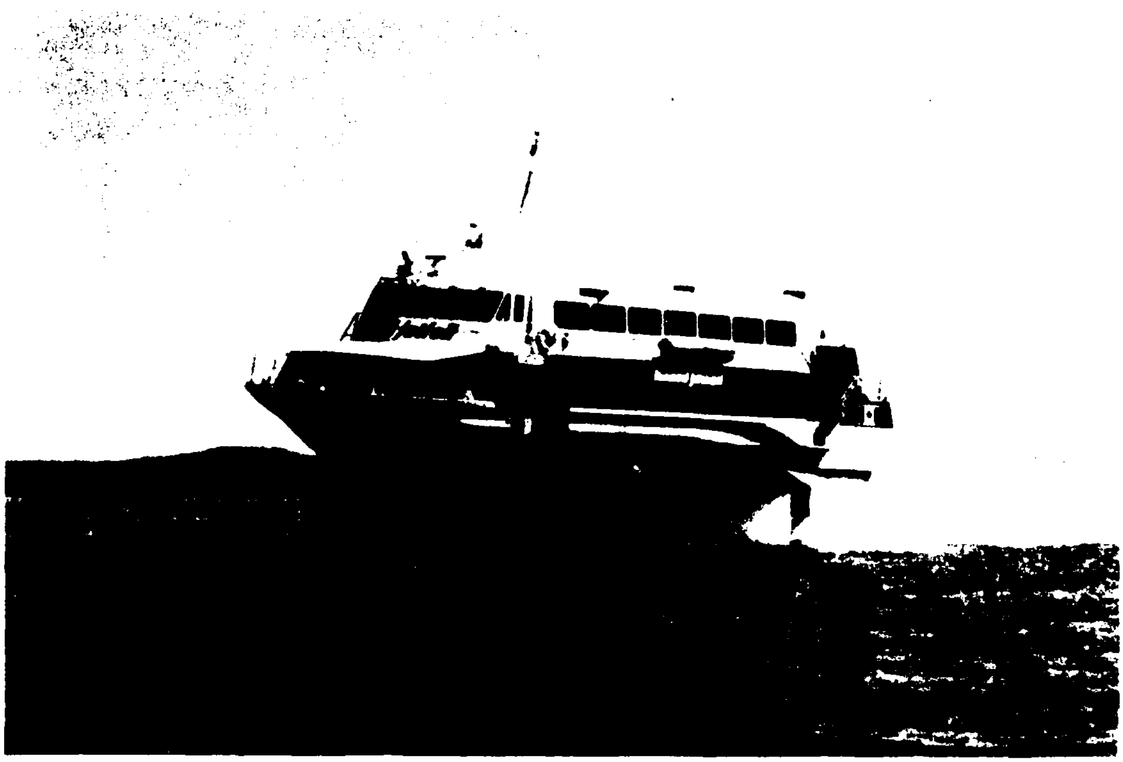

Figure 11. Approaches to the problem of minimizing wave effects

27. If the dynamic motions of a survey boat are measured and correlated with time during a survey section run, the corresponding depth measurements taken during that run can be corrected for motion-induced errors. This is the approach followed by most other researchers who have studied the problem and is the approach primarily followed in this study. Vertical motion measurement techniques are examined in Part II.

28. As an alternative approach, if wave-induced vertical motions of a survey boat are minimized by hull design, the dynamic vertical movement may be reduced to a level where no correction of depth measurements is necessary, or the correction can be reduced significantly. This approach follows a general measurement rule that it is usually good practice to eliminate errors in a given measurement to the extent practical and then to make corrections in the data for known and measurable error factors. Various hull designs that have been tested in an effort to reduce surveying errors are shown in Figure 12. Air cushion vehicles such as the Corps' *Rodolf* (Sims 1982), shown in Figure 12a are examples of a hull suspension design that has a very significant effect on wave-induced boat motion. The air cushion acts as a hull suspension system with a lower natural frequency than a displacement hull. A boat hull

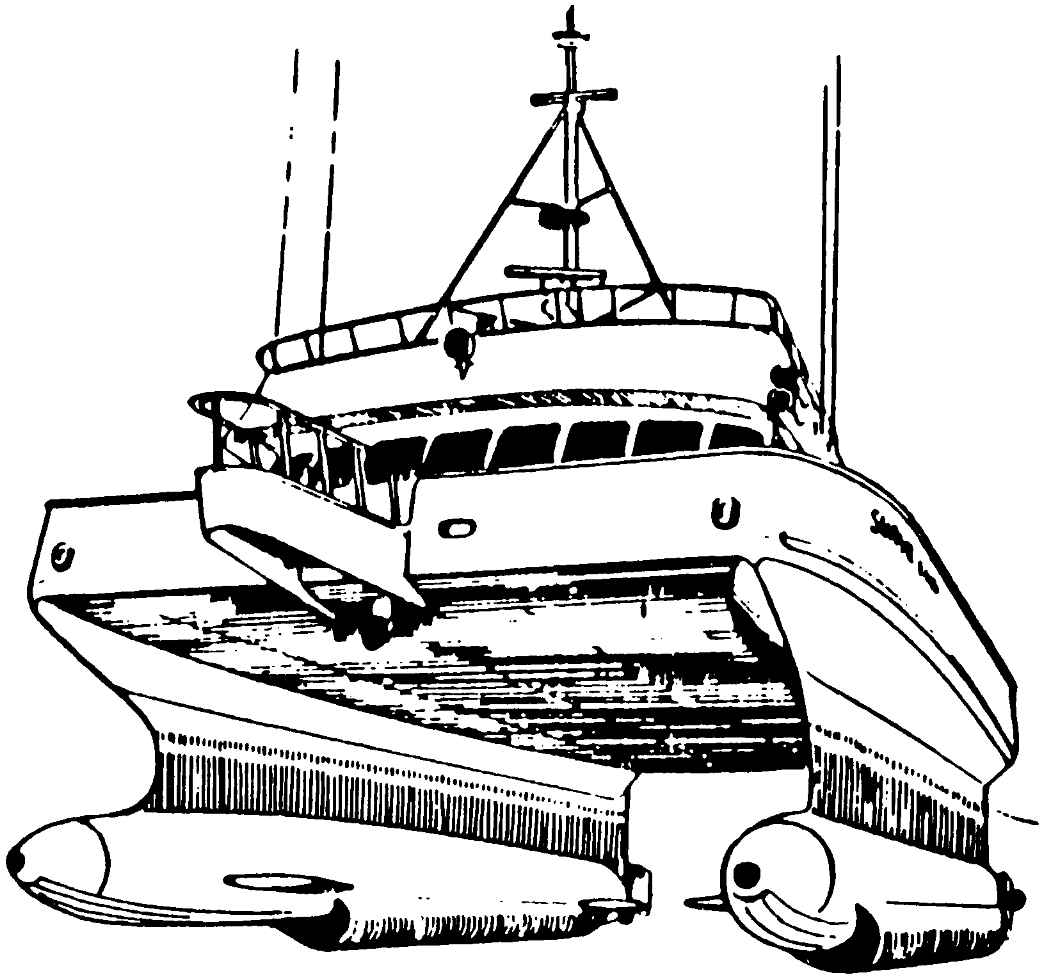



a. Air cushion hull vessel, *Rodolf*, currently in use in the US Army Engineer District, Portland (from Sims 1982)

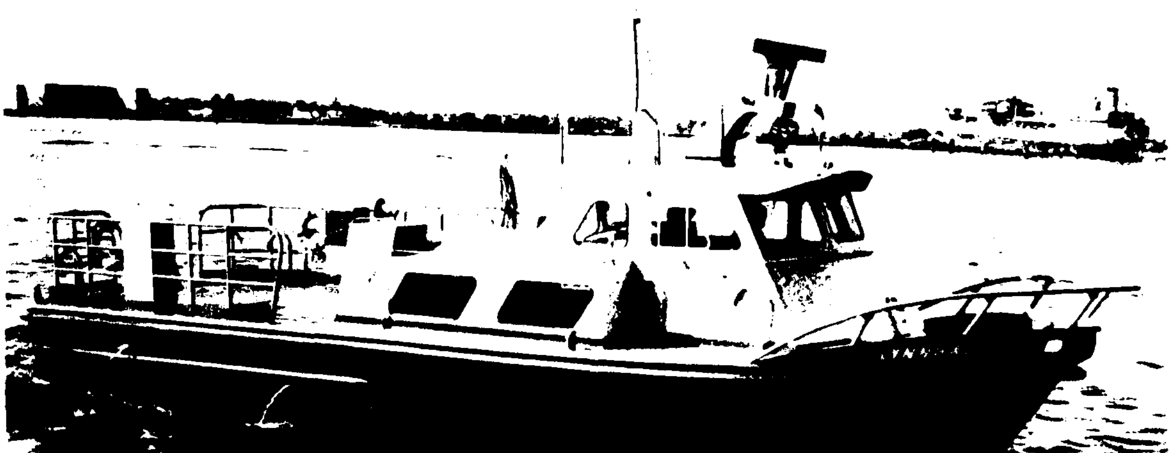


b. Hydrofoil-supported vessel

Figure 12. Survey boat hull designs (Continued)



c. Small waterplane area twin hull (SWATH) vessel
(from Drummond 1985)



d. Displacement hull vessel

Figure 12. (Concluded)

acts as a low-pass mechanical filter for wave forces. Lowering the natural frequency of the hull suspension system lowers the "filter pass band" and reduces the motion effect of waves with frequencies higher than the natural frequency of the suspension system. If a boat encounters wave frequencies near the natural frequency of the hull suspension system, the boat motion can exhibit displacements that are even larger than the wave displacement. Probably the best known example of wave action minimization using air cushion hulls is the English Channel ferry.

29. Another boat hull technique in use is called a hydrofoil, shown in Figure 12b. This supports the boat on a set of underwater "wings" much like an aircraft and is effective only when the boat is in motion at fairly high speeds. Hydrofoil-supported boats are much less buffeted by surface waves than are displacement hull boats. They have been experimented with in the past, primarily as a means of increasing boat speed. For survey boats, typically designed to make transverse channel measurements, the rapidly changing water depth as the vessel approaches the shore probably is unsuitable for hydrofoils. If a survey boat were designed to make longitudinal channel measurements, a hydrofoil stabilization system might be both technically feasible and operationally effective in providing improved depth transducer stability. Another possibility to be explored could be a retractable hydrofoil design, much like retractable keels on sail boats, which might be a practical compromise for survey boats.

30. A displacement hull design that reduces wave effects on hull motion is shown in Figure 12c. This design is effective statically as well as dynamically and has been tried on a large-scale experimental basis by the US Navy. This small waterplane area twin hull (SWATH) design (Drummond 1985, Bechly 1985) uses twin submerged flotation tanks for support of a cabin area that remains above water. Small hydrofoils attached to the flotation tanks are used for dynamic control of heave, pitch, and roll. The SWATH design has a relatively small change in static flotation force for waves smaller than the spacing between the flotation tanks and the deck. The SWATH-type hull is therefore much more stable than a displacement-type hull, shown in Figure 12d, when operating in sea states within its design range. Elimination of vertical boat motion is preferable, when practical, to correcting erroneous depth measurements after a survey is performed. Due to the depth of the submerged tanks, this hull design would probably be more practical for survey boats

designed for longitudinal survey, which are run at more constant depth, than those planned for transverse surveys.

31. Hull design can be an important factor in survey boat effectiveness and accuracy of results. Experiments with boat hull design are ongoing in many places in this country and others. The possibility of improving hydrographic surveys by improved hull design should not be overlooked. For the purpose of this study, however, the investigation of hull design is not considered in detail.

32. Separating the function of transporting the depth transducer from the other functions of the conventional survey boat is another approach that opens some avenues to improve performance. Using conventional displacement hull design (as shown in Figure 12d) in a remote-controlled (RC) boat would probably not help in alleviating wave-induced errors. However, if RC transducer vehicles are used, their hull design can be much more specialized, utilizing optimizations not possible when human safety is paramount as in conventional survey boats. For instance, RC transducer vehicles could be built like torpedoes and run either at the surface or submerged such as the one shown in Figure 13. A near-neutral-buoyancy torpedo-shaped hull would be considerably less wave-tossed than a conventional displacement hull. RC depth transducer vehicles would need to contain only a propulsion system and enough electronic equipment to measure and transmit basic signals. The bulky data processing equipment and human operator support equipment would remain on the manned control boat.

33. An RC transducer vehicle has the disadvantage that it requires an inherently more complex system than conventional manually controlled boats. The advantages, however, are numerous enough to make this approach worth considering. Some of the advantages are as follows:

- a. Improved depth accuracy is achievable.
- b. Small RC vehicles can be used in shallower water and get closer to shore than big survey boats.
- c. Survey personnel could stay out of shipping lanes most of the time, letting the RC vehicle make the crossings.
- d. Small RC vehicles would create less wake than larger boats at the same survey speed.
- e. Several RC vehicles could be controlled from one large survey boat.

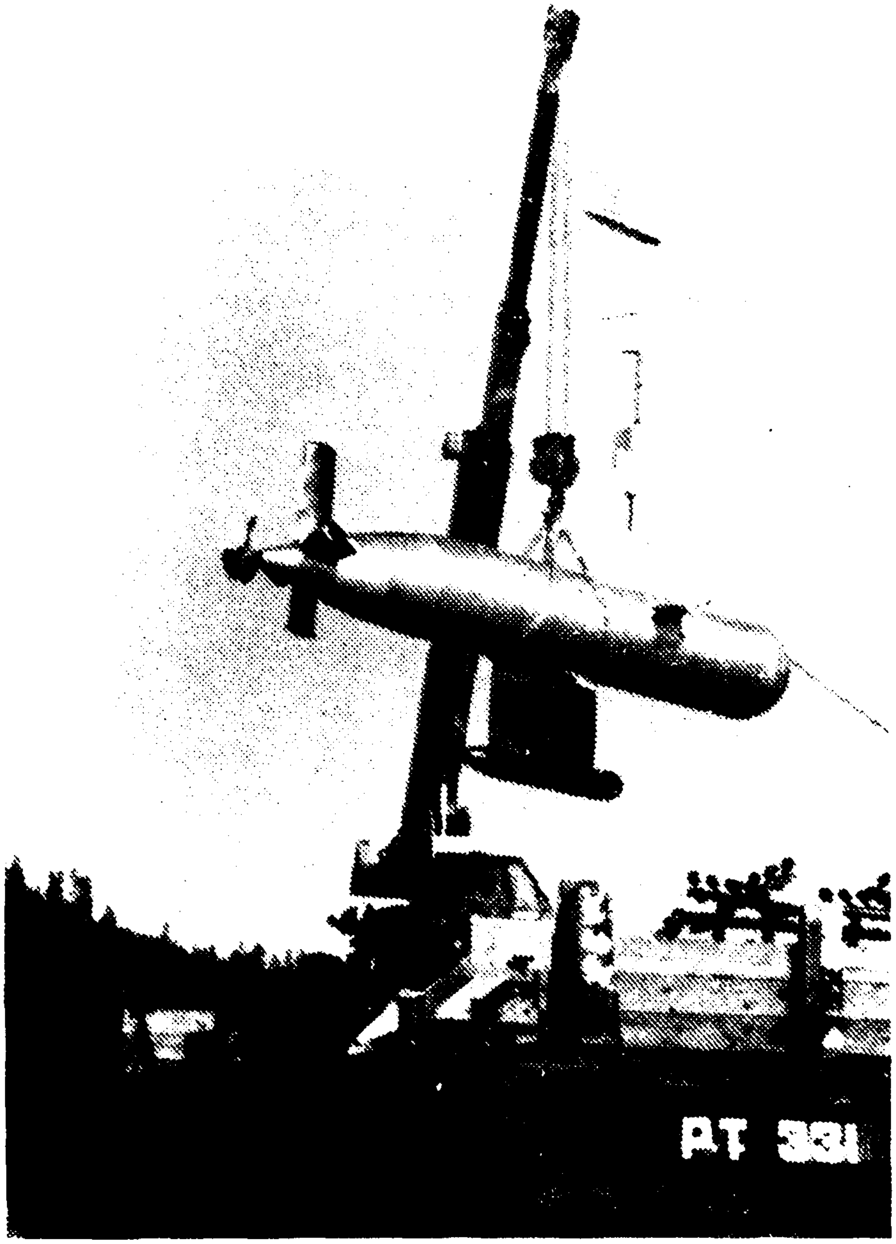



Figure 13. Remote-controlled transducer vehicle

34. An RC depth transducer vehicle thus offers some potentially important advantages in hydrographic survey accuracy and effectiveness. The investigation of RC vehicle design, however, was considered beyond the scope of this study.

35. A cable-towed subsurface transducer platform is another method whereby the transducer can be physically separated from the boat hull.

Side-scan sonar, magnetometer, and subbottom profilers typically use this approach. A towed transducer platform has operational problems that have discouraged use of this technique for depth measurements. For Districts that have significant wave problems and are willing to use longitudinal survey lines, the use of towed depth transducers may be an optimum compromise. For the purpose of this study, however, the investigation of towed depth transducer platforms was considered too specialized to warrant pursuing at this time.

## PART II: MEASUREMENT TECHNIQUES

### Vertical Motion Measurement Techniques

36. A large number of different techniques have been tested for measuring vertical motion of boats (and of other vehicles such as planes and trucks). Factors peculiar to water-surface-based measurements, however, impose constraints not significant in land or air vertical motion measurements. Water-surface-based measurements also have some freedoms and a reference not possible on land or in the air. Consider first the basic vertical reference for hydrographic surveying--the water-surface geoid. This reference is a curved surface, approximating a sphere, with local irregularities due to gravity anomalies. For depth measurement purposes, gravity anomalies can be disregarded because the waterway surface is the surface against which depth is referenced, not against a hypothetical geoid. The water surface supporting the survey boat can likewise be adjusted at any point in time to allow for very low frequency variations caused by tide or river stage. Tide and stage corrections can be made with confidence if the survey section is within a mile of the gage and there are no intervening flow constrictions. Properly placed tide gages will also provide local corrections for seiches that occur as the result of seismic and atmospheric disturbances.

37. There is a range of wave frequencies for which heave correction is required. Waves, swells, and bores with wavelengths shorter than approximately 20 times the distance from tide gage to boat must be dealt with on the boat (heave correction). For very short wavelength waves, the tide gage reading has no significance because the dynamic water surface has many high and low sections between a given boat location and shore gage site. Waves with periods of less than 1 sec have little effect on the vertical motion of a survey boat. There is also a maximum wavelength that necessitates heave correction. With earlier NOAA studies as a guide, waves with a 100-sec period can probably be considered as the longest wavelength waves that will normally cause significant heave errors (NOAA 1974). Wave-level changes with periods longer than this can normally be measured at a shore point and used in the same manner as a tide correction. The frequency range of interest for survey boat heave measurement is thus from 1 to 0.01 Hz.

38. Measuring vertical boat motion can be accomplished by a number of

techniques, each of which has limitations on accuracy and practicality. The following paragraphs will describe the general techniques that are of possible use for measuring vertical boat motion and the existing state of the art for each particular technique. The practicality of using a specific technique under a given set of field conditions is addressed. The following tabulation gives a summary of vertical motion measuring techniques that are considered. The tabulation shows, in abbreviated form, several fundamental factors related to motion measurement. It also itemizes the math involved in converting each specific type of measurement from a physical form to a useful form in engineering units and illustrates how time-related errors in velocity and acceleration measurements will be magnified by each successive integration.

| Measurement | Measurement Parameter | | |
|---|---|---|---|
| Form | Displacement* | Velocity** | Acceleration |
| Optical | Laser levels<br>Electromechanical optical trackers<br>Video motion trackers | N/A | N/A |
| Acoustic | Vertical beam transit time | Vertical beam Doppler | N/A |
| Inertial | N/A | N/A | Vertically oriented linear accelerometer<br>Gyros |
| Mechanical | Altitude transducer | N/A | N/A |
| Radio and microwave | Transit time | Doppler Radar | N/A |

* Scaling required to convert to engineering units.

** Single integration and scaling required to convert to engineering units.

Double integration and scaling required to convert to engineering units.

## Vertical Displacement Measurement Techniques

39. Direct measurement of the vertical motion (displacement) of a survey boat is theoretically possible using any one of a half dozen or more techniques. In this section, these techniques and the limitations of each will be examined. Direct measurement of vertical motion provides data that require

only simple algebraic processing to give results in engineering units. Direct displacement measurement circumvents the drift-prone processing inherent in techniques that are based on measurement of velocity or acceleration.

40. Survey boat crews using transits for positioning have all observed the boat bouncing in the eyepiece when there is significant wave action (Figure 14). For tidal action and swells, a good transit operator would be able

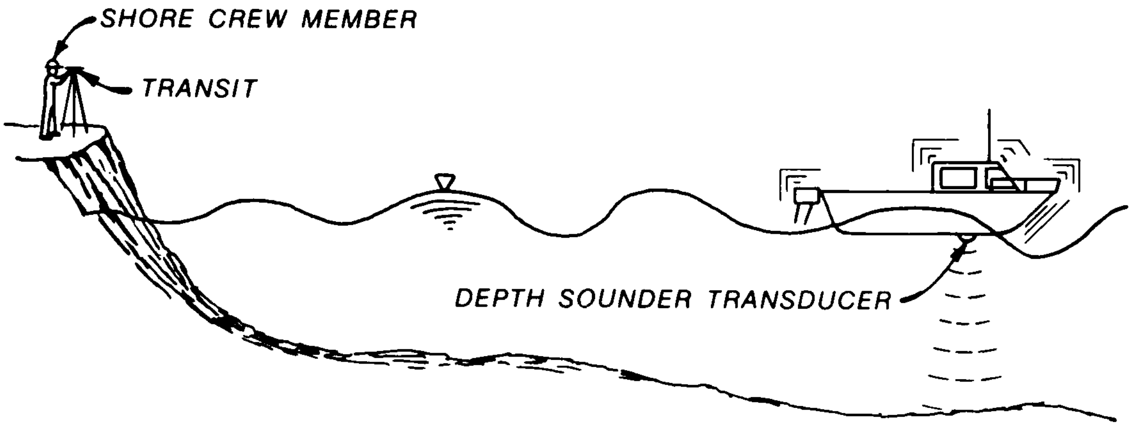



Figure 14. Use of transit for positioning survey boat

to manually track a survey boat and read both vertical and horizontal angles. In addition, wave frequencies low enough to be manually tracked with precision and ease are also slow enough to be measured at the shore. However, the frequency of the wave action of interest is too high to track manually. Manual optical tracking of the vertical angle thus does not offer a useful solution to the heave problem; therefore this method was not considered further in the study.

41. Automatic electrooptical tracking systems have been available for a number of years. Appendix A lists the names and addresses of manufacturers and suppliers of survey equipment. Companies such as Sanders Corporation and GTE Sylvania have built high-precision, high-speed optical trackers for military purposes (Figure 15). The GTE Sylvania tracker, as an example, uses a high-power laser for determining target position (which includes elevation). The reflected laser energy is also used in electromechanical control loops to keep the tracker pointing at a corner cube reflector array on the target aircraft. Cost of military type optical trackers has stymied use in hydrographic survey work. Also the high-power lasers normally used would be unacceptable in a civilian application because they are not eye-safe.

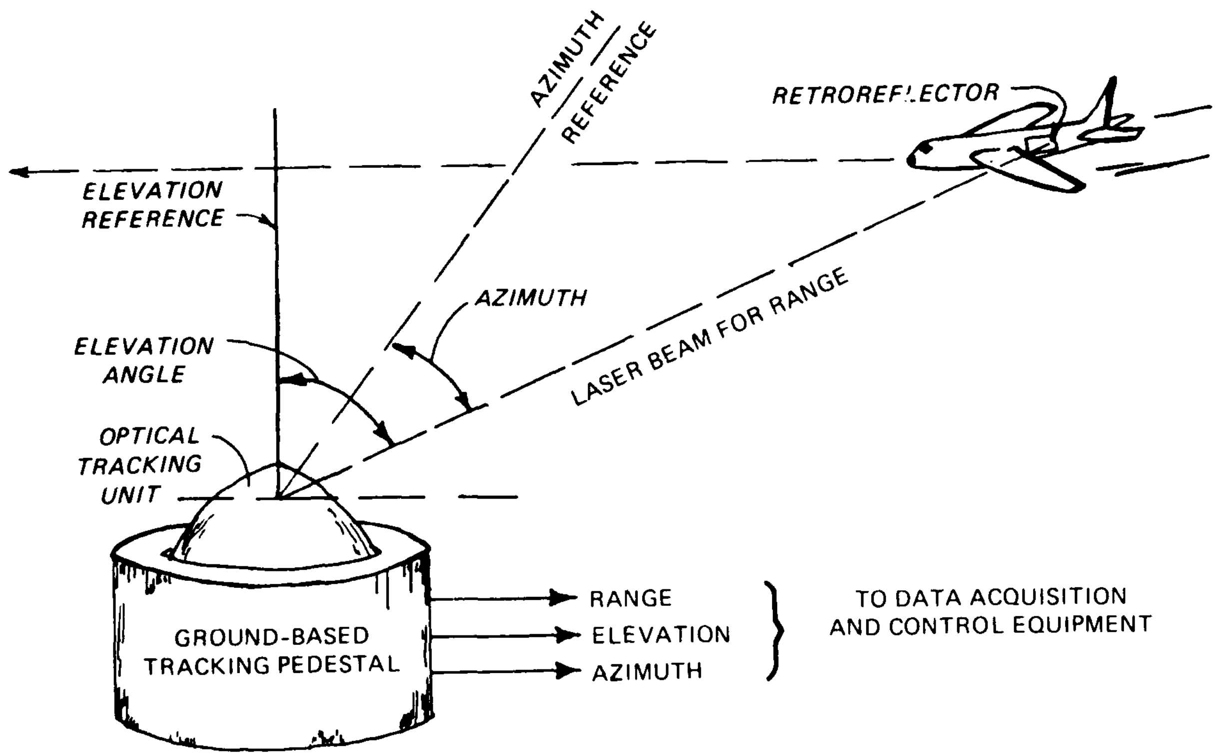



Figure 15. GTE laser aircraft tracking system

42. Krupp Atlas Elektronik Corporation introduced an electrooptical automatic tracking system in 1983 that is aimed at the hydrographic survey market. The Krupp Atlas Polarfix,* as currently manufactured, measures range and azimuth. The cost of this automatic optical tracking system is relatively high ($140K) compared with a manual tracking system ($60K), but it is much less costly than previously available military systems. Krupp Atlas has announced their intention to add a vertical angle measurement function to the Polarfix. If this feature is successfully developed, and if the cost does not increase drastically, a system that can measure vertical change (heave) as well as range and azimuth will become commercially available. The Polarfix system incorporates a video image detection subsystem that can electronically measure high rate-of-change, small-angle motion. Use of this technology eliminates the need for the optical head to mechanically track the target with high precision and at a high angular rate. As long as the optical head mechanical drive can keep the target image in the field of view of the video

* Polarfix is a registered trademark of the Krupp Atlas Elektronik Corporation.

detector the system will function. In the current version of Polarfix, the azimuth measurement that is transmitted is the sum of the mechanical position of the optical head and the video detector output. This combination of technologies should be ideal for measuring heave (at short ranges), which will appear as a small, rapidly changing vertical angle superimposed on a larger, slowly changing vertical angle. The Polarfix is designed with an optical beam density level that is defined as eye-safe in both the United States and most European countries. Equipment use will thus not be restricted by safety concerns as is the case with higher-powered lasers.

43. The Polarfix system (or any shore-mounted optical tracking system) will have constraints that affect the measurement of heave much more than azimuth. Heave measurement resolution is needed in centimetres compared with a tenfold, less rigorous requirement for the horizontal position. Vertical and horizontal accuracy degrades as a linear function of range for an angle measuring system. This degradation with range, in the case of heave resolution, will probably limit potential use of the Polarfix positioning system as a heave compensation to short ranges (perhaps 1 or 2 km). All of these comments are simply speculation until Krupp Atlas actually completes the development. The Krupp Atlas system was not available in 1980 when heave measurement systems were being considered for field evaluation.

44. Several video-type optical tracking systems are commercially available and are designed to make measurements of equipment vibration. These systems electronically track a very small light (or target) attached to the equipment and measure the small change in vertical and horizontal angle produced by machine motion. OPTRON* (Nesty 1980; Lieb and Rocchio 1973) is an example of a commercially available video optical tracker. Video optical trackers were studied for potential use in heave measurement systems. To evaluate this technique would have required a major investment in development of a mechanical servo drive for the optical head. Previous experience in measuring machine vibration with video optical trackers caused concern about overwater refraction problems and practical stability of the optical mount. It was concluded that pursuing development of a heave measurement system based on a video optical tracker was not appropriate considering the high development costs and the many uncertainties. The Krupp Atlas Polarfix system may

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* OPTRON is a registered trademark of Universal Technology, Inc.

disprove this conclusion. Its development will be monitored for possible future consideration-application.

45. Another optical technique initially considered was the use of a laser leveling instrument. These instruments are commercially available and are used for many static leveling applications. The US Air Force has used a laser level for measuring airfield runway deviation from a flat plane. The Air Force technique involves measuring the vertical motion of a test vehicle that is driven along the runway. A thin beam of light is projected by a laser located at the end of a runway. The test vehicle is outfitted with a mast having optical detectors along its length. As the test vehicle moves, different detectors on the mast are illuminated by the laser.

46. A commercial leveling system based on this principle is marketed by Spectra-Physics as the Laserplane.* A rotating laser head projects a narrow beam of light that sweeps a horizontal plane. A detector mounted on the mast of a moving vehicle seeks the height where the laser beam strikes the mast. The Laserplane is designed for ground-leveling purposes but may be useful for short-range hydrographic surveying. The standard Laserplane is limited to a horizontal range of 1,000 ft. The company also makes special models capable of ranges of several thousand feet. Standard Laserplane units use a laser sweep rate of 300 rpm, which gives five updates of elevation per second. This is adequate for nearly all hydrographic survey work. The rapid advance of technology may make this approach useful for hydrographic surveying on small rivers within a few years.

47. Satellites open the possibility of an entirely different approach to heave measurement. Vertical displacement measurement from an earth surface point is constrained to the detection of very small angles as an indirect measurement of vertical displacement. From the vantage point of an earth orbit satellite, however, the vertical displacement measurement can be made directly rather than indirectly through an angle (DeLoach 1985). The soon-to-be-completed GPS has already been used in ways not foreseen when originally planned. The originally specified Z-axis dynamic accuracy was contemplated to be approximately 1 m, which is not adequate for heave correction. New techniques now under development have the possibility of providing dynamic Z-axis accuracy adequate for heave correction. These techniques use the differential

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* Laserplane is a registered trademark of Spectra-Physics.

mode of operation and require a receiver to be located at both a reference point on shore and the survey boat. Heave correction will, of course, require 24-hr visibility of the satellites which will not be realized until the full complement of satellites is put into orbit. Delays in the space program due to the space shuttle setback make predictions about the availability of 24-hr GPS visibility difficult to make. The GPS can, of course, already be used to update the vertical and horizontal positions of vertical reference points because these can be measured statically and at whatever time of day the GPS satellites are visible. Geosynchronous satellites (in equatorial orbit) may have a potential for providing measurements that can be used for heave compensation. Interferometer techniques are already being used to measure small changes in distance from specially equipped satellites. A suitably equipped synchronous satellite could provide a direct measure of the change in slant range from the satellite to the survey boat. From the 22,000-mile height of a synchronous satellite, the change in slant range has a large vertical component. With appropriate corrections for geometry and horizontal boat motion, it should be possible to convert the change in slant range to vertical boat motion. While intriguing, the use of synchronous satellites for heave measurement was considered to involve such large development costs that it was not practical to pursue this approach.

48. Atmospheric pressure can give a coarse indication of altitude. The accuracy of this technique is much too poor for heave motion measurement. No further consideration was given to this technique.

## Vertical Velocity Measurement Techniques

49. Velocity is mathematically related to displacement so that the measurement of one of these parameters as a time-varying element makes it possible to compute the other. Thus, when it is difficult or impossible to measure displacement directly, it may be possible to measure velocity and compute displacement (displacement is the first integral of velocity). This is discussed in detail in Part IV. A large number of velocity transducers are commercially available but most require a two-point physical attachment, as is the case with displacement measurement. It is not practical to have any physical connection between a survey boat and a reference point, so velocity transducers requiring this sort of connection are automatically excluded from

consideration as potential indirect heave measuring instruments. Seismic type velocity transducers are also excluded because these are limited to measurements where the motion has a very small peak-to-peak displacement (less than 1 in. typically).

50. Velocity of a moving vehicle can be measured with respect to a signal source or reflective surface by using the Doppler effect. Doppler velocity measurements make use of the fact that the frequency of a received signal is shifted away from the frequency transmitted if the receiver and transmitter are moving with respect to each other. As an example, highway patrol "speed guns" are a widely used Doppler instrument. Doppler speed logs and Doppler navigators are additional examples of commercial instruments using this principle of operation. These widely known examples use the Doppler effect to measure horizontal velocity. The same principle can be used to measure vertical velocity of a boat or plane with respect to a reflective surface. The Doppler effect works with light, microwaves, and acoustic energy. An aircraft can use light or microwaves but not acoustic energy. A boat cannot use light or microwaves underwater because of the severe attenuation of these forms of energy in water. Acoustic energy is ideal underwater because of low attenuation of the signal.

51. A commercially available Doppler system, the NAVITRONIC HTC-1,* is manufactured by NAVITRONIC Corporation (Nielsen 1985). This system processes the depth transducer signal to determine the Doppler shift due to heave. In operation, the NAVITRONIC depth measuring system equipped with a Doppler heave unit transmits alternate pulses with different pulse widths. The shorter width pulse is used to derive a depth measurement. The longer width pulse is used to derive a vertical motion measurement. It is necessary to measure only the time of arrival of the reflected pulse to determine depth. Only the leading edge of the pulse is needed to measure transit time, and the depth pulse can therefore be very short--only a few cycles. More information must be extracted for a reflected pulse in order to determine Doppler shift than is the case where only the leading edge is detected. A pulse must contain many cycles for a Doppler detector to function with reasonable accuracy. This is why the NAVITRONIC Corporation Doppler heave unit must use different pulse widths for the depth and heave pulses. The Navitronic system is the only

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* HTC-1 is a registered trademark of NAVITRONIC Corporation.

known commercially available Doppler heave unit.

52. Using the same transducer for Doppler heave measurement and depth measurement is the simplest approach mechanically, but it forces some compromises on both measurements. Depth measurement is optimized by using the narrow beam transducer and short pulse width. Doppler measurement using a single vertical transducer is optimized by using a broad beam transducer and a relatively long pulse width. A broad beam width reduces the effect of pitch and roll on the reflected pulse energy that returns to the transducer.

53. Doppler navigators and Doppler speed logs use a transducer assembly separate from the depth transducer. A separate Doppler transducer assembly reduces the number of design compromises that must be made compared with the situation where the depth transducer is used for both Doppler and depth. WES made some preliminary experiments using a commercial Doppler navigator to assess the feasibility and the practicality of using such a unit as a heave measuring instrument. A description of these experiments is given in Part IV. Also discussed are the theory of Doppler, the other components of a Doppler system, and how the measurement is converted to vertical displacement.

## Acceleration Measurement Techniques

54. Acceleration measurement is fundamental to the functioning of inertial navigators and inertial guidance systems. Acceleration measurement has the tremendous advantage that the only reference required is the reference mass built within the accelerometer housing itself under known starting conditions. If the vertical acceleration of a boat is measured as a function of time, vertical motion (displacement) of the boat can be computed by double integration of the measured acceleration. Thus, fundamentally, the use of acceleration to determine vertical boat motion is straightforward. In actual practice, the implementation of an inertial reference is very complex.

55. Accelerometers are manufactured to match a wide variety of applications. A description of the many mechanisms and techniques used in accelerometer construction is beyond the scope of this report. All accelerometers, whatever their construction, provide a signal output that is proportional to the force acting on the reference mass within the accelerometer housing. The accuracy with which this signal represents the desired parameter is a function

not only of the accelerometer accuracy but of the way in which this instrument is coupled to the vehicle being monitored.

Unstabilized accelerometer

56. If a single accelerometer is mounted directly on the hull of a survey boat, it will measure the motion of the boat hull along the sensitive axis of the accelerometer. An accelerometer rigidly mounted on a boat, with its axis vertical when the boat is level, will approximately measure vertical motion. Pitch and roll of the boat will cause the accelerometer to point in directions other than vertical, and the resultant output signal will include gravity effects as well as vertical motion effects. An accelerometer cannot distinguish between the acceleration due to gravity and the acceleration due to boat motion. Since the acceleration due to gravity (1.0 g) is generally much larger than the acceleration due to heave (0.1 g maximum for a 0.10-Hz, 2-ft wave), tilt of the accelerometer can cause a serious error in the measurement. The error due to accelerometer tilt is nonlinear, with the gravity-induced signal being a cosine function of the degrees off vertical. For small angles of tilt the error may be low enough that an unstabilized accelerometer signal can be useful. For instance, a well-designed towed transducer unit may have much less pitch and roll than the survey boat towing it, and a direct-mounted accelerometer may give useful heave correction signals. Unstabilized accelerometers have the advantage that they are much lower in cost than stabilized accelerometer systems.

57. An accelerometer mounted on a partially stabilized transducer platform can be useful for some heave corrections. A simple accelerometer assembly is much less costly than the stabilized accelerometer systems described in the following paragraphs. A commercial system using accelerometers for heave compensation without vertical stabilization is the Atlas Heco 10 and Atlas Deso 20* (Jurisons 1985). It should be noted that the gravity-induced error due to tilt, in an unstabilized accelerometer, is always in one direction regardless of whether the boat is pitching bow down or up or heeling port or starboard. Tilt error always induces a signal indicating a false downward boat motion (reduced gravity). Integrating a tilt-contaminated accelerometer signal to get vertical velocity and displacement compounds the tilt error.

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* Atlas Heco and Atlas Deso are registered trademarks of Krupp Atlas Elektronic Corporation.

Some types of errors, such as random noise, can be alleviated by smoothing techniques. Tilt-induced errors cannot be compensated for unless additional measurements are made. Unstabilized accelerometers do not provide heave signals sufficiently accurate to be used for general Corps hydrographic survey work.

Pendulum-stabilized accelerometer

58. Tilt-induced errors in a vertical axis accelerometer can be alleviated to a large extent by mounting the accelerometer on a properly designed pendulum platform. In the absence of horizontal acceleration, a pendulum will hang vertically. An accelerometer mounted on the pendulum will also maintain a vertical axis. This principle can be used to design a pendulum-stabilized accelerometer unit suitable for a survey boat. Pendulum-stabilized accelerometer systems are more costly than unstabilized accelerometer systems described previously but less costly than other stabilization and compensation techniques described in the following paragraphs. Horizontal acceleration introduces a tilt error in a pendulum-stabilized system. Thus, boat turns, stops, and starts affect the pendulum vertical accuracy for a short period of time. A small survey boat in narrow channels will be maneuvering very rapidly and a pendulum-stabilized accelerometer system will not be satisfactory. A large survey boat in a broad channel or bay, running long survey lines at constant speed, will probably find that a pendulum-stabilized accelerometer system works well. The heave compensation system described in Part III of this report is a pendulum-stabilized accelerometer unit.

Gyro-stabilized accelerometer

59. Tilt-induced errors in a vertical axis accelerometer can be largely avoided by mounting the accelerometer on a platform that has the plane of the platform maintained in a constant attitude. A gimbaled gyroscope will maintain a constant attitude regardless of the motion of a carrying vehicle. A gyroscope can thus be used to keep the axis of an accelerometer in a known orientation in spite of vehicle pitch and roll. Some gyro-stabilized accelerometer packages mount the vertical accelerometer directly on one of the gyro inner gimbals. Some more complex packages use a gyro sensing unit as a separate package and use the signal from the gyro unit to operate servos that in turn keep the accelerometer mounting platform stable. A servo-driven stabilized platform does not have the sensor size and weight limits that a direct coupled gyro-stabilized platform has. A servo-driven stabilized platform can

also be used to keep the depth sounder transducer pointed vertically. Heave compensation requires only a single-axis stabilization. A stabilized platform to be used for navigation purposes must be stabilized in all three axes. Three-axis stabilization can be achieved with two gyros. An example of a mechanically coupled two-gyro-stabilized platform is given in Figure 16. This unit has output signals for pitch, roll, and yaw and three orthogonal accelerometer signals. The example shown in Figure 16 is designed for aircraft use.

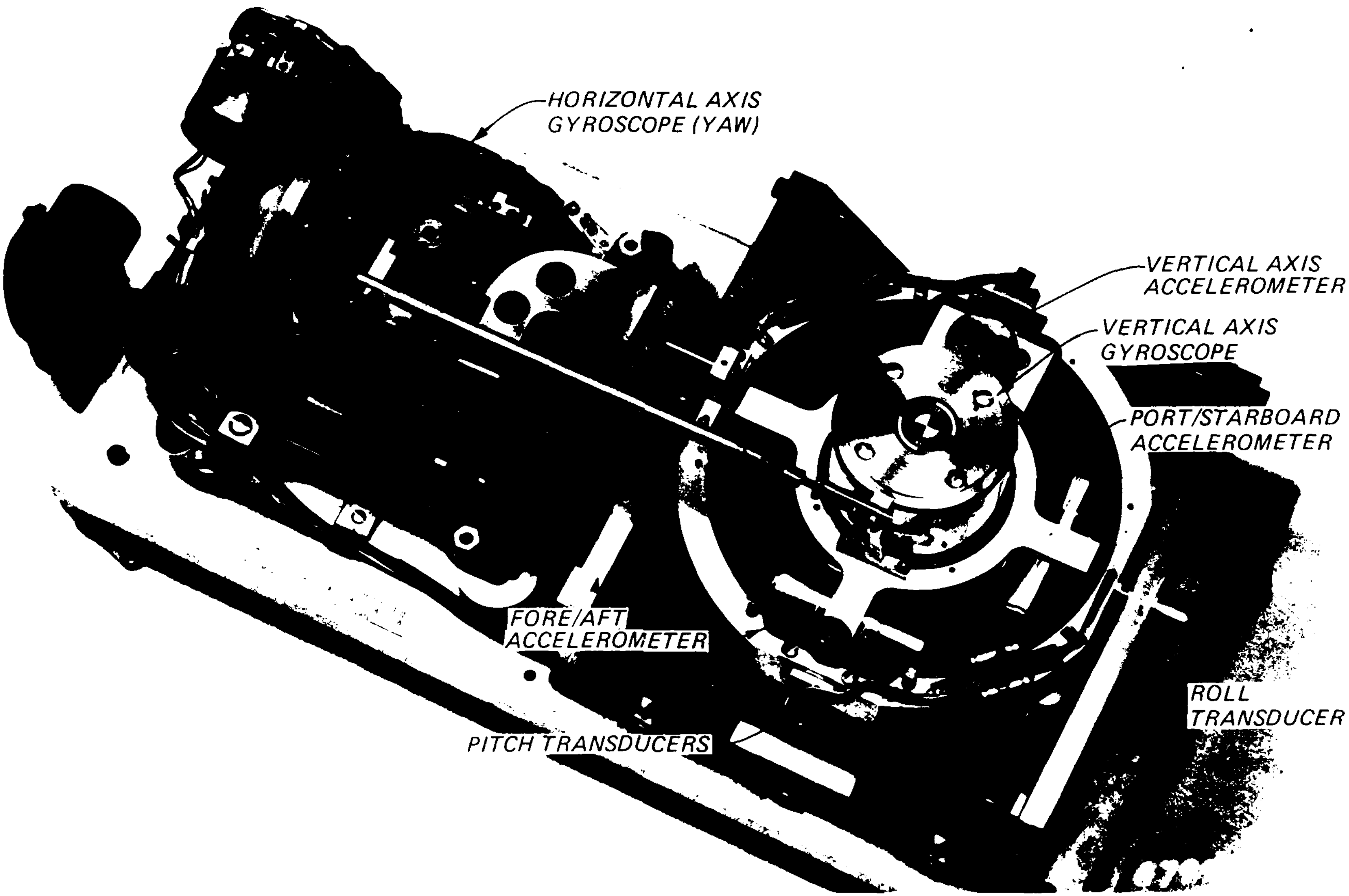


Figure 16. Mechanically coupled two-gyro-stabilized platform

# PART III: FIELD EVALUATION OF HIPPY 120

60. NOAA has been studying heave correction techniques for a decade or more. The inertial techniques discussed in paragraphs 58 and 59 were examined theoretically and several experimental systems tried (NOAA 1974, 1979; Pryor 1982). The NOAA conclusion was that a pendulum-stabilized heave correction system was the most cost-effective solution for their type of work. This conclusion was based on 1977 technology. A pendulum-stabilized system is intermediate in performance between an unstabilized accelerometer system and a gyro-stabilized system. A pendulum-stabilized system is lower in cost and avoids gyro-stabilized system operational and maintenance problems. The Corps has some large survey boats that operate under conditions similar to those experienced by NOAA coastal launches. It was deemed expedient to make use of NOAA development work for heave compensation in pursuing the evaluation of heave compensation systems suitable for Corps applications. Discussions between NOAA/NOS and Corps/WES personnel led to an agreement to make a cooperative evaluation of a pendulum-stabilized heave compensation system, the HIPPY 120, manufactured by Datawell Corporation, The Netherlands.

## Controlled Testing at NOAA/NOS

61. The HIPPY 120 (Pryor 1982, Huff 1979, Enabit 1982) purchased by the Corps from Datawell was initially delivered to the NOAA/NOS facility in Riverdale, Maryland, for controlled laboratory tests in 1980. Datawell Corporation delivered three HIPPY 120 units at the same time; two were NOAA units and one was a Corps unit. This shipping arrangement was in accordance with an agreement between Corps and NOAA personnel made at the time the Corps unit was purchased for NOAA to make laboratory tests on all three units as a group. This testing gave NOAA a better evaluation of the manufacturing consistency of Datawell Corporation for this product. It also gave the Corps a much better evaluation of the HIPPY 120 performance under controlled conditions than would have been possible with Corps test facilities. Each of the three HIPPY 120 units was installed in sequence in a large machine available at NOAA for testing wave-measuring buoys. With some mechanical modification to allow for a change in case size, the wave buoy test machine was usable for monitoring the unit's capability to measure boat heave, pitch, and roll. Results of the NOAA laboratory testing were very encouraging (Pryor 1982).

## Installation of HIPPY 120 on Survey Boat *Shuman*

62. The US Army Engineer District, Philadelphia, was one of the early advocates for the development of heave correction systems. While the HIPPY 120 was undergoing laboratory tests at NOAA, the Philadelphia District indicated it would be interested in evaluating the heave correction instrument. When the laboratory tests at NOAA were completed, the Corps HIPPY 120 was shipped to the Philadelphia District in 1983 for installation on the survey boat *Shuman*. The *Shuman* was selected because it frequently surveys in the Delaware Bay where significant wave action is common. Another factor favoring the *Shuman* was the very large cabin space available. It is a catamaran hull survey boat, nominally 65 ft in length. Due to the catamaran hull, it has an unusually wide beam (Figure 17).


Figure 17. Rear view of the survey boat *Shuman*

63. The HIPPY 120 was installed in the left side of the boat cabin as close to the depth transducer as possible. Figure 18 shows the HIPPY 120 unit in the *Shuman* cabin. It was bolted to the deck following the recommended installation procedures in the instrument manufacturer's manual (Datawell). The HIPPY 120 is a heavy 300-lb instrument that must not be dropped, banged against bulkheads, or otherwise subjected to shock during handling. The installation crew for this instrument must therefore have the equipment and

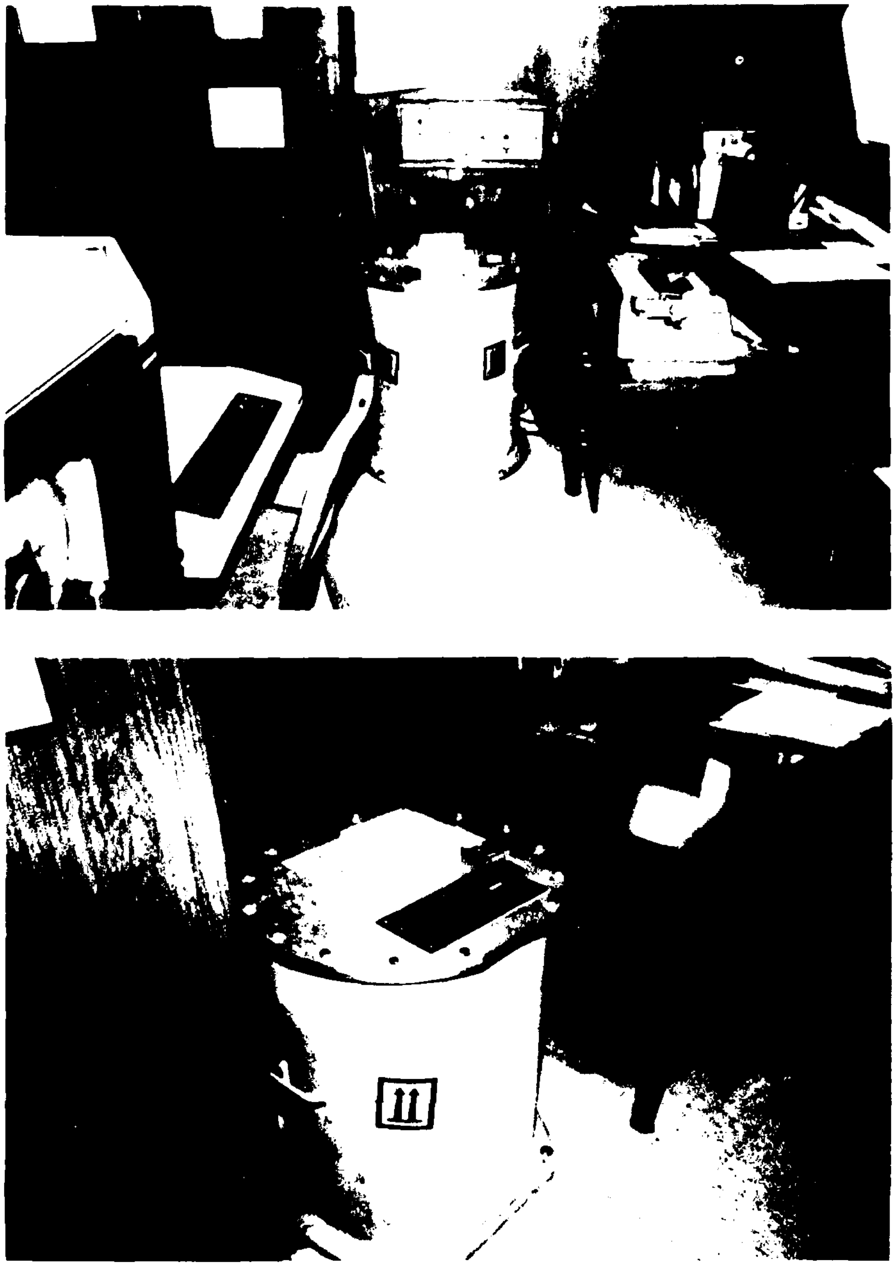

Figure 18. HIPPY 120 as installed in *Shuman*

skill necessary to move and place heavy equipment in a carefully controlled sequence.

64. Due to the cabin and hull configuration, it was not possible to place the heave instrument directly over the depth transducer. This introduced a small error in the instrument output as it was not subjected to exactly the same motion as the depth transducer. The effects of misalignment of depth transducer and heave measuring instrument were analyzed in detail by NOAA (1974). For the *Shuman* installation, the effect of the misalignment was minimized because of the wide beam associated with the catamaran hull.

65. The HIPPY 120 was connected to the existing computer-based survey system aboard the *Shuman*. Signal transfer is via an RS-232C cable, thereby requiring an RS-232 port on the computer. Figures 19 and 20 show the *Shuman* survey system components. A block diagram of the *Shuman* survey system including the HIPPY 120 is shown in Figure 21.

66. The automated survey system aboard the *Shuman* has many components and functions that can be described in more detail. For instance, the depth is measured using a Ross digital depth sounder (Ross 1985, Dickson 1973). The depth measuring subsystem is shown in the right-hand electronic equipment cabinet of Figure 20. During a survey, an on-line analog record of depth is made on the Ross Fineline* recorder. A close-up of this depth recorder is shown in Figure 22. Signals from the depth transceiver are converted to computer compatible form by the Ross digitizer which is also one of the components in the depth sounder cabinet. The analog chart and the digitizer display give the crew members a continuous real-time indication of the depth independent of the computer-based functions. The depth sounder calibration is periodically verified using a "bar check" procedure. Figure 23 shows the bar being lowered for a bar check aboard the *Shuman*. Once the bar is submerged, it is moved forward until it is situated at a known depth directly below the depth sounder.

67. Horizontal positioning of the survey boat is accomplished with a Cubic DM 43** two-range distance measuring system (Dickson 1973, Enabit 1982). This unit is located in the pilot's cabin and is not visible in the figures shown here. The Cubic DM 43 range display gives the pilot a continuous

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* Fineline is a registered trademark of Ross Laboratories, Inc.
** Cubic DM is a registered trademark of Cubic Precision Corporation.

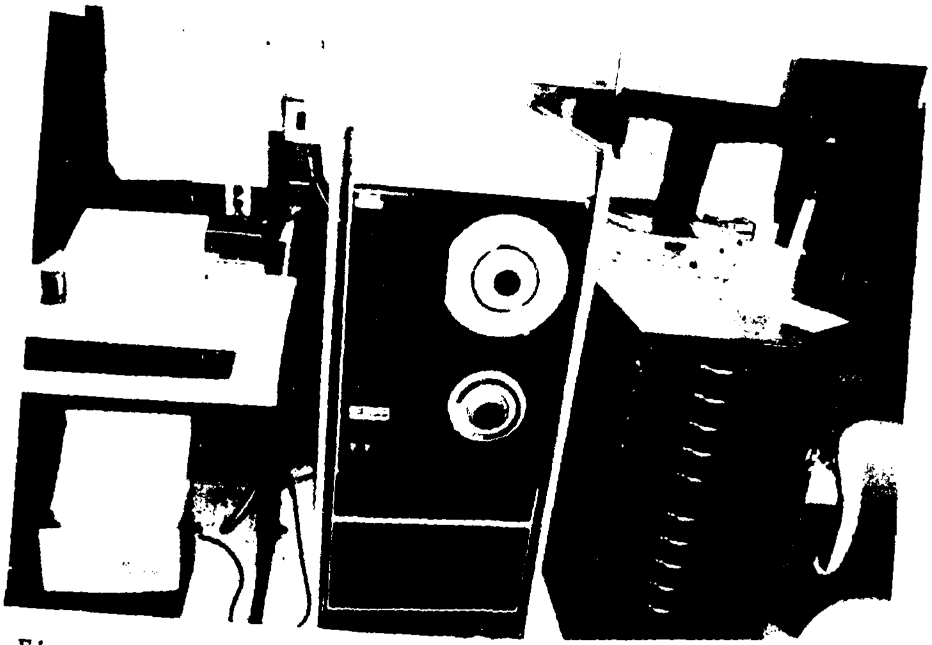

Figure 19. Automated survey system magnetic tape recorder


Figure 20. Automated survey system components

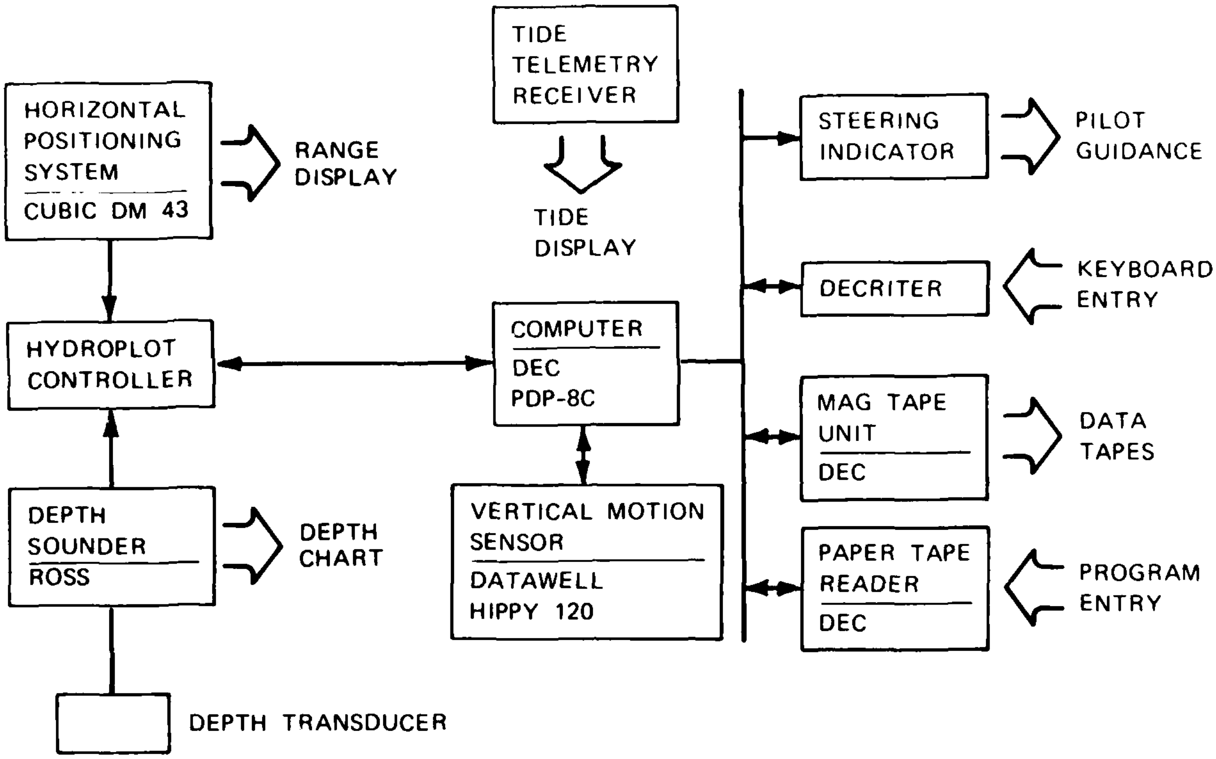


Figure 21. Automated survey system with heave correction

Figure 22. Ross Fineline recorder

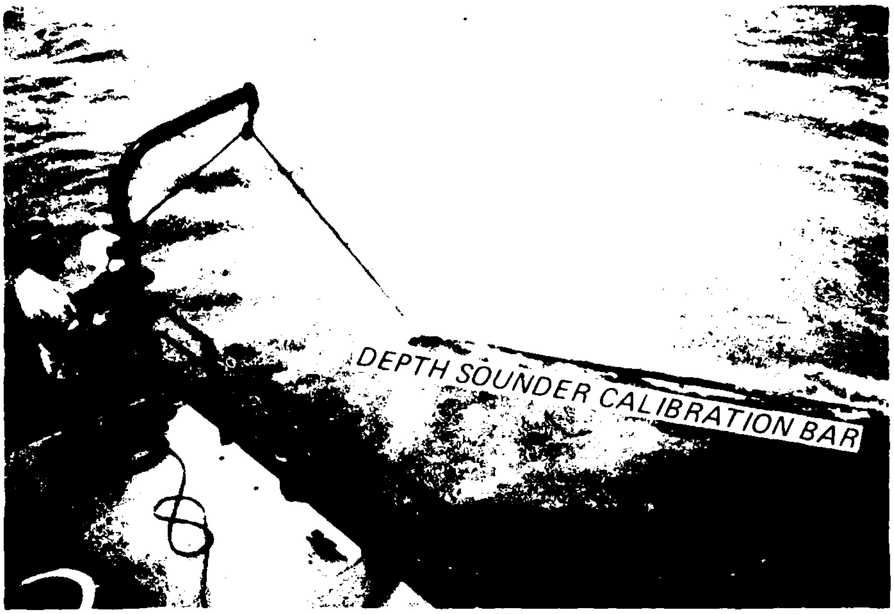


Figure 23. Bar check of depth sounder

real-time indication of the distance to two shore stations independent of the computer.

68. Digitized values of depth and range are sent to the DEC Hydroplot* controller (Wallace 1973) that provides an interface between the measurement components and the computer. The Hydroplot controller is the top panel in the left equipment rack shown in Figure 24. The controller is also used to manually enter draft and tide values into the system. The tide is measured by an automatic tide gage, such as an Aquatrak** gage (Spies 1982), which is set up at a shore station near the survey areas. The tide data are transmitted by radio link to a receiver on the *Shuman*. The receiver is the top case on the right-hand equipment cabinet in Figure 24. Currently, the boat crew must manually enter the updated tide data into the Hydroplot controller. Automatic input of the tide data from the receiver to the Hydroplot controller is planned as a future improvement.

69. Survey data are recorded on the DEC magnetic tape unit shown in Figure 19. Survey results are plotted on the plotter shown in Figure 24. This particular system can plot charts either on-line or from stored data after a survey is completed.

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* DEC Hydroplot is a registered trademark of RACAL-Decca Survey Systems, Inc.
** Aquatrak is a registered trademark of Bartex, Inc.

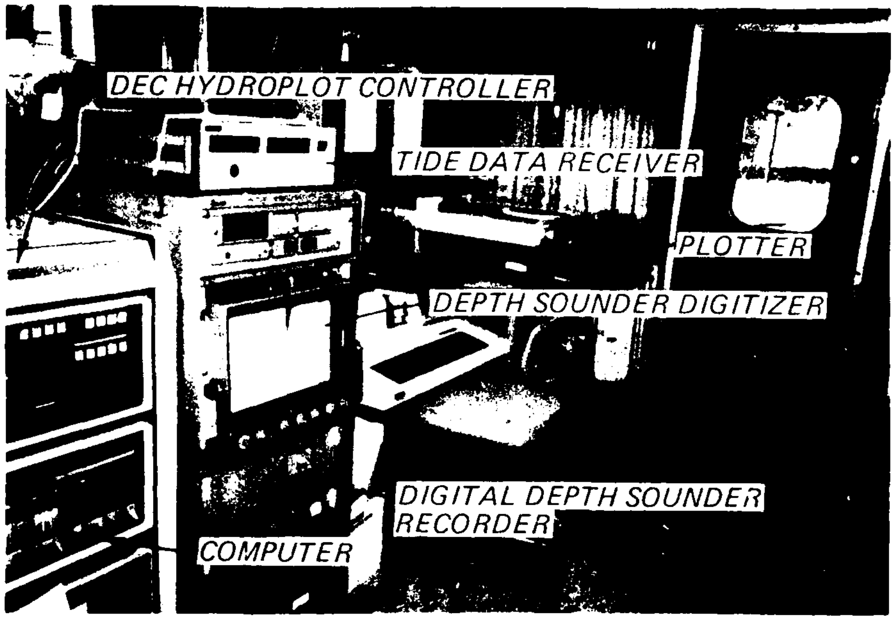



Figure 24. Automated survey system peripheral components

70. Incorporating the heave motion unit in the *Shuman* automated survey system required that the system software be rewritten to include the following added heave-related functions:

- a. Interrogate the HIPPY 120 signals each time a depth measurement is taken.
- b. Store each heave motion data block plus time on magnetic tape along with the depth data.
- c. Retrieve depth and heave data from the tape file.
- d. Plot charts using the depth data corrected for vertical motion.

71. The HIPPY 120 provides two heave output signals as well as pitch and roll signals. One of the heave signals is an on-line signal that is double-integrated and is referred to as an analog output. The other heave output is delayed by 77 sec and is digitally processed. The delayed, digitally processed signal has much better compensation for drift than the on-line analog signal. The delayed signal cannot, of course, be used for on-line heave compensation; it can be used only during postprocessing because of the inherent time lag.

72. The software written to work with the HIPPY 120 allows the operator to select either on-line heave or the delayed heave signal for depth correction during postprocessing. Experience to date indicates that errors in the on-line heave signal are unacceptably large, and depth correction should be

done during the postprocessing phase using the digitally processed and delayed heave signal. The software, as currently written, records the pitch and roll signals but does not use these for calculating pitch- and roll-induced errors.

## Experience of *Shuman* Crew with the HIPPY 120

73. The HIPPY 120 remained aboard the *Shuman* for more than a year. It was exposed to the temperature changes inherent in a yearly cycle at the latitude of Philadelphia. It was also exposed to the salt, air, humidity, and vibration that is to be expected on a survey boat. The HIPPY 120 continued to function properly after a year of this exposure, so it can tentatively be concluded that it is adequately rugged and reliable for the intended survey application. Because it is a mechanically passive device (there are no motors or high-speed bearings in the HIPPY 120), this type of unit can be expected, in general, to have a better maintenance record than a gyro-stabilized heave system.

74. Software redesigned to include the HIPPY 120 in the existing *Shuman* hydrographic survey system has not functioned as well. Intermittent hang-ups of the system plagued operations and discouraged the boat operators from routine use of the complete system with the new software. These intermittent problems plus pressure to complete the regular Philadelphia District Survey Branch operations caused postponement of efforts to get the heave correction system fully checked out and integrated into the routine survey work.

75. A quantitative evaluation of the HIPPY 120, or any heave system, is difficult to make under real survey conditions. An evaluation consisted of the following:

- a. Several survey lines were run across an area of the Delaware River with a relatively smooth, flat, stable bottom. These initial surveys were made in relatively calm water.
- b. The same survey lines performed in step a were repeated during a period of significant wave action.
- c. Using the survey line data collected in step a as a base, the raw data collected in step b, and the HIPPY 120 heave-corrected data, a four-way comparison was made.

76. A less complete comparison was made of the signals from the heave correction system using waves generated by the passage of a large ship. An arbitrary section line was chosen (in this case it was the last one of the

day's survey work). This section line was run in the main navigation channel of the Delaware Bay, during a period when the water surface was relatively calm. The depth chart for this section is shown in Figure 25a. The *Shuman* crew then waited for a large freighter to pass by and generate waves. The section line was rerun with ship-induced wave action present. Wave action modifications to the depth chart for this section are apparent in Figure 25b. Ideally, the repeat section line should have been run when the main waves were in the center and flatter portion of the channel. This proved impractical because of safety considerations. By the time it was judged safe to run the section line astern of the passing ship, the main wake wave was already reaching the edge of the channel. The depth charts of Figure 25 thus show the greatest wave-induced differences at the channel edges and little difference in the center of the channel. Having the waves dominate at the channel edge, however, emphasizes a very important point. A rough bottom chart cannot be smoothed to take out wave action without concealing bottom projections. In the examples given in Figure 25, the true bottom cannot be determined from one of the depth charts alone, even with two depth charts to compare.

77. Figure 26 contains a plotted chart showing the bottom cross section taken during the section line run made before passage of the ship. Figure 27 presents a digitized plot of depths before and after heave correction. The data were taken from the two section lines mentioned. The digitized lines are offset so that they do not overlap. Line A is the cross section without waves and with no heave correction applied. Line B is the cross section with waves from the passing ship and with no heave correction. Line C is the cross section with waves from the passing ship and with the plot corrected using the on-line analog heave output from the HIPPY 120. Line D is the cross section with waves from the passing ship and with the plot corrected using the delayed digital heave output from the HIPPY 120. The wave action during this example was not continuous as natural waves would be. These plots thus do not show significant differences except at a few points. An important point illustrated here is that the software is designed so that the surveyor does not have to use the heave correction data unless he wants to.

78. Due to the pressure of regular operations, the loss of key personnel, and software problems, the Philadelphia District was unable to continue the experimental work with the HIPPY 120. The US Army Engineer District, New York, expressed interest in trying the HIPPY 120 on one of their survey boats

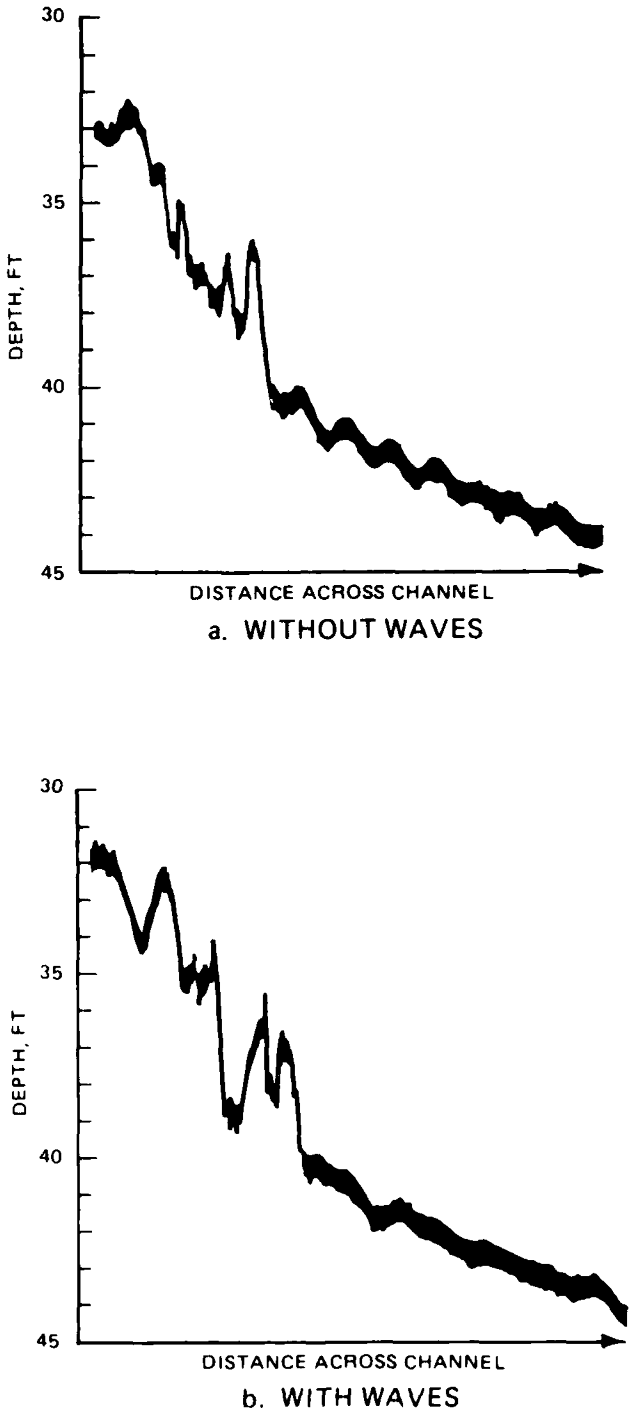



Figure 25. Effect of wave action on depth measurement

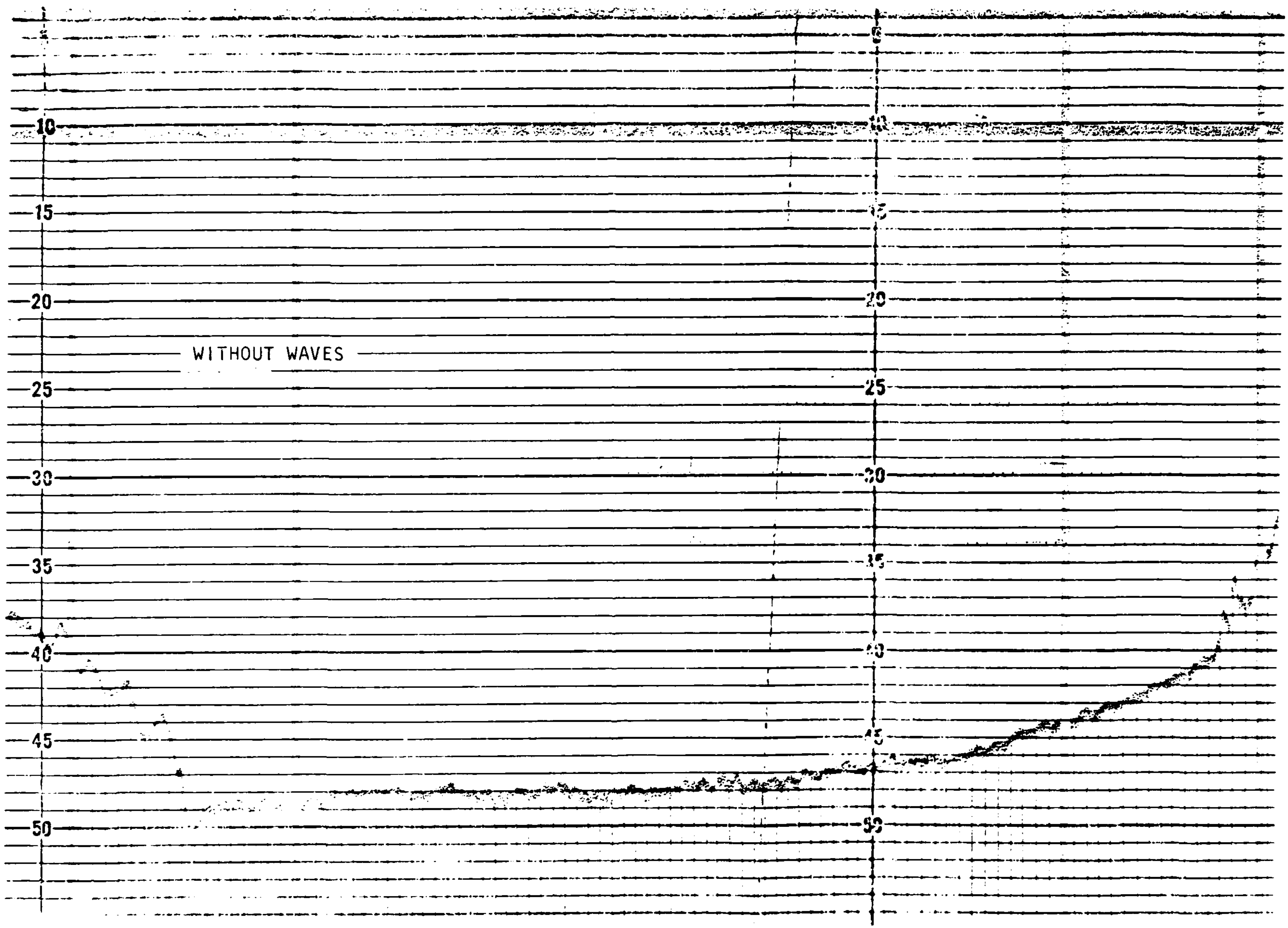



Figure 26. Chart plot of channel cross section

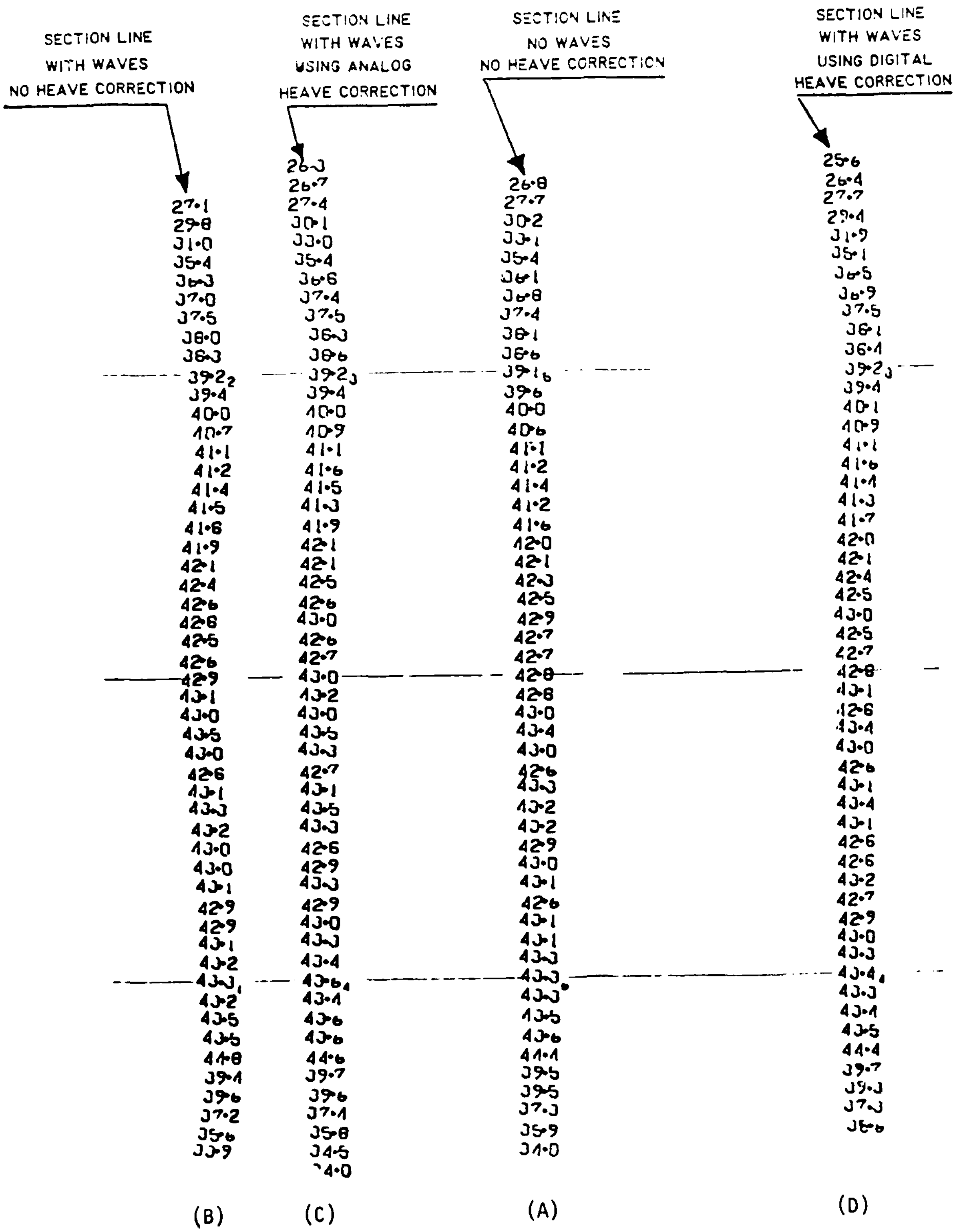



Figure 27. Comparison of survey plots with and without heave correction

following the Philadelphia District decision to discontinue their work. In June 1984 the HIPPY 120 was shipped to the New York District and installed in the survey boat *Hatton*. A new computer-based survey system was installed in the boat at the same time the HIPPY was installed. The new computer-based system was supplied with software designed to merge the HIPPY data with the depth and position data. During field trials, however, the HIPPY failed during self-test. The New York District has not had the time or funds to pursue the development work any further at the time of this report. Evaluation of the effectiveness of the HIPPY 120 as a practical field instrument is thus still inconclusive. Since two Districts have tried it and have been unsuccessful, it obviously is not an easy instrument to use.

79. The two HIPPY 120 instruments purchased by NOAA/NOS (at the same time the Corps purchased one) were installed on survey launches (Pryor 1982) and are functioning satisfactorily. The NOAA/NOS installations are on larger boats with bigger staffs and with more funding. NOAA/NOS survey work covers areas where wave action is more prevalent and larger in amplitude. Their need for heave correction is thus more compelling than that of the Corps. They have therefore been willing to invest the staff and funding necessary to make a technological development functional. Corps Districts must recognize a similar level of urgency if they are to use existing heave correction technology. It took many years, and a major investment, to bring computers onto survey boats as an operational tool. A high level of effort, similar to that for incorporating computers in survey systems, will be necessary to make heave correction a practical tool.

## PART IV: EXPERIMENTS WITH THE DOPPLER VERTICAL MOTION MEASUREMENT

80. Acoustic energy transmitted from a depth sounder transducer travels through water at a constant velocity, if uniform conditions are assumed in the path of the sound from the source to the receiver. This constant velocity of propagation of acoustic energy in water is the principle on which depth sounders are based.

81. Depth sounders use only a small part of the information implicit in the signal returned to the receiver. In addition to transit time information, there is amplitude information that is related to the bottom reflectivity (or density). There is also frequency shift information that is related to boat motion. Doppler speed logs and Doppler navigators have used the frequency shift principle for many years to determine horizontal motion. Frequency shift due to source and receiver motion can be used to determine vertical motion if the geometry of the transducers is appropriate.

### Principles of the Doppler Vertical Motion Measurement

82. The basic Doppler principle states that relative motion between a sound source and a sound detector (or receiver) will cause a change in the frequency of the detected signal with respect to the source frequency. When the source and receiver are moving toward each other, the frequency is shifted higher; when they are moving apart, the frequency is shifted lower. This frequency shift is directly proportional to the relative velocity between the signal source and the receiver.

83. For a stationary receiver and a signal source moving toward it, the received signal frequency is

$$f_r = f_s \left( \frac{c}{c - v} \right) \tag{1}$$

where

$f_r$ = receiver frequency, Hz

$f_s$ = source frequency, Hz

$c$ = velocity of sound in water, ft/sec

$v$ = source (boat) velocity, ft/sec

With the velocity of sound in water approximately 4,800 ft/sec, then the frequency shift due to a boat velocity of 1 ft/sec will be small but measurable.

84. The tremendous utility of the Doppler principle for boat motion measurement rests on the fact that acoustic energy transmitted from the boat and reflected from the bottom can be detected by a boat-mounted receiving transducer. The Doppler principles discussed in the previous paragraphs apply with bottom-reflected energy, but the frequency shift detected in this case is twice that detected by a fixed receiver. For the condition in which the source and receiver move together with respect to a reflective surface, the frequency received is

$$f_r = f_s \left(\frac{c + v}{c - v}\right) \tag{2}$$

$$f_r = f_s \left(\frac{1 + \frac{v}{c}}{1 - \frac{v}{c}}\right) \tag{3}$$

$$f_r = f_s \left(1 + \frac{2v}{c} + \frac{2v^2}{c^2} + \frac{2v^3}{c^3} + \ldots\right) \tag{4}$$

Since the boat velocity is very small compared with the velocity of sound in water, the higher order terms in Equation 4 become negligible for most purposes. For a boat velocity of 10 ft/sec, the first order frequency shift term $2v/c$ is $0.4 \times 10^{-2}$. The second order term $2v^2/c^2$ is $0.9 \times 10^{-5}$ frequency shift. The second (and higher) order terms are thus so small for typical boat speeds that the Doppler shift can be approximated by the equation

$$\Delta f = f_s \left(\frac{2v}{c}\right) \tag{5}$$

where

$\Delta f$ = difference between the transmitted and received frequency, Hz

$v$ = velocity of the source and receiver transducer, ft/sec

Irregularities and slopes of the bottom surface do not affect the Doppler

shift. Each point on the bottom that is reflecting energy is stationary to the sound energy impinging on it.

85. Doppler speed logs and Doppler navigators make use of transducer beam geometry to detect a Doppler shift that is proportional to a directional vector of the boat motion. The Doppler shift due to horizontal motion of the boat, as shown in Figure 28, can be described by the equation

$$\Delta f_H = \frac{2f_s}{c} (v_x) \cos \theta \qquad (6)$$

where

$\Delta f_H$ = Doppler shift along the beam axis due to horizontal boat motion

$v_x$ = forward horizontal boat velocity, ft/sec

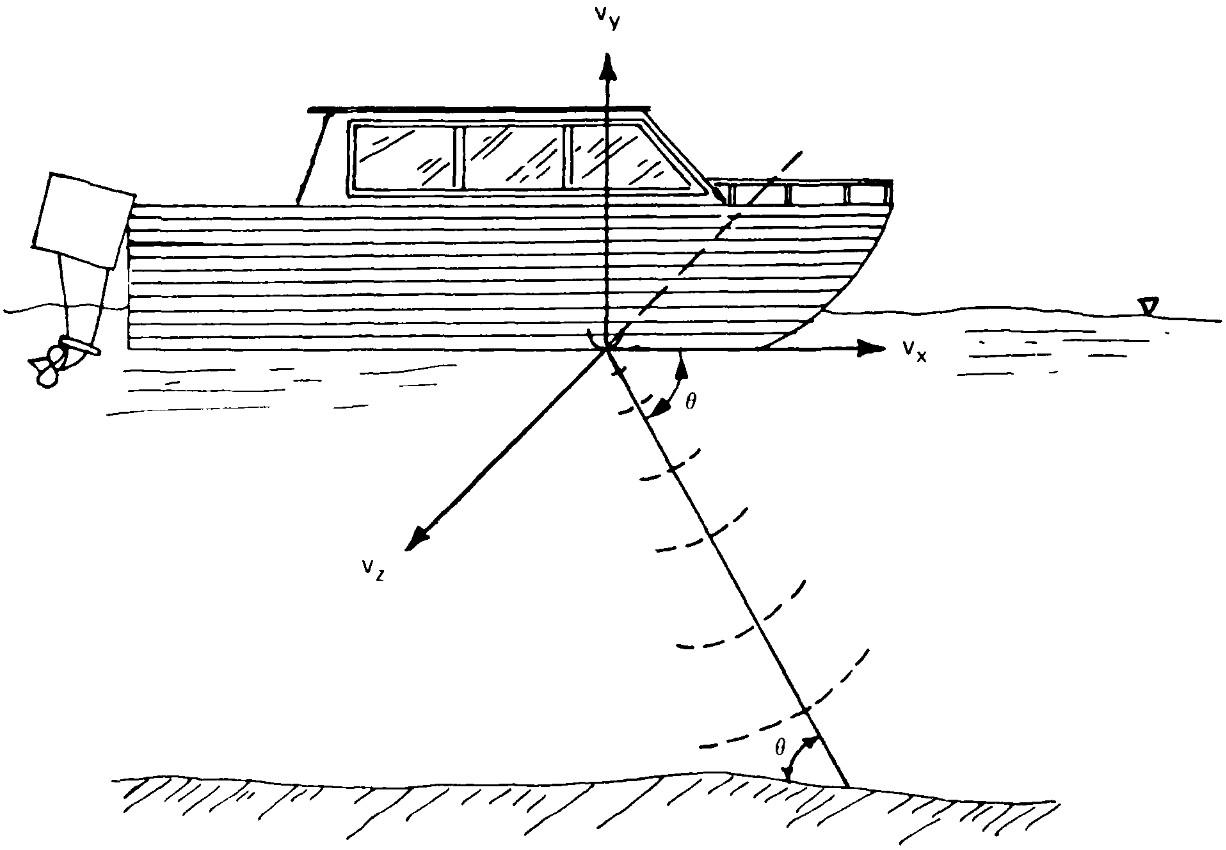



Figure 28. Doppler shift due to boat motion

The Doppler shift due to the vertical motion of the boat is

$$\Delta f_V = \frac{2f_s}{c} (v_z) \sin \theta \qquad (7)$$

where

$\Delta f_V$ = Doppler shift along beam axis due to vertical boat motion

$v_z$ = vertical velocity of the boat

These equations assume that all the acoustic energy is projected along the beam axis. Doppler navigators and speed logs use the relatively narrow beam widths (3 deg); therefore this assumption is reasonable and justified. In normal boat operation, both the vertical motion and horizontal motion occur together and the resultant Doppler shift of a single beam will be the sum of the individual components.

$$\Delta f = \frac{2f_s}{c} (v_x \cos \theta + v_z \sin \theta) \qquad (8)$$

For a well-aligned (straight vertical) depth transducer and no pitch and roll of the boat, the effect of horizontal motion on the Doppler shift is relatively small as shown in Figure 29a.

86. Doppler navigators make use of a beam pattern geometry (called a JANUS configuration) that allows the effect of horizontal and vertical motion to be determined individually and the unwanted component canceled. If two transducers are mounted in the pattern shown in Figure 29b, the motion components in the Doppler shifts of the fore and aft signal beams are as described in Equations 9 and 10, assuming forward horizontal motion and upward vertical motion of the boat.

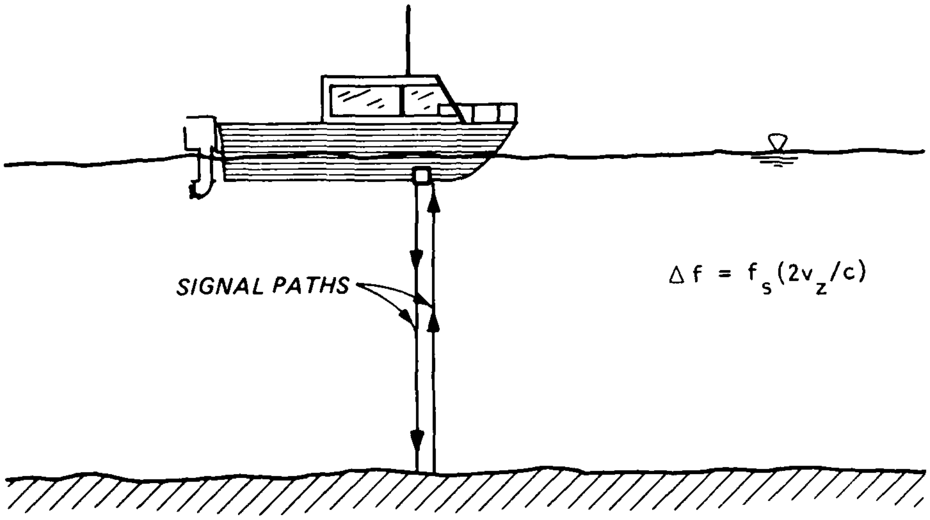
$$\Delta f_F = \frac{2f_s}{c} (v_x \cos \theta - v_z \sin \theta) \qquad (9)$$

$$\Delta f_A = \frac{2f_s}{c} (-v_x \cos \theta - v_z \sin \theta) \qquad (10)$$

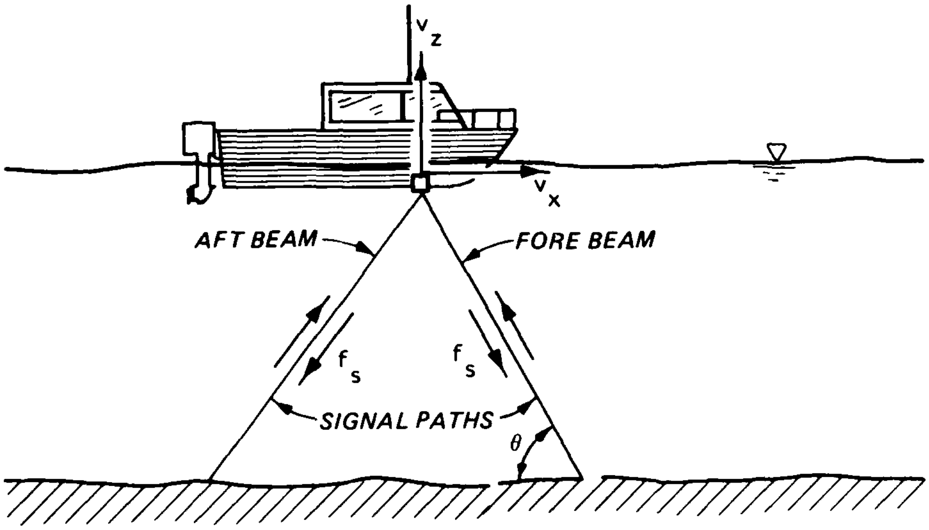
where

$\Delta f_F$ = fore beam Doppler shift

$\Delta f_A$ = aft beam Doppler shift




a. Vertical beam transducer configuration




b. JANUS angled beam configuration

Figure 29. Effect of horizontal and vertical motion on the Doppler shift

Fore/aft velocity ($v_x$) is a function of the <u>difference</u> between the fore Doppler shift and the aft Doppler shift. The vertical motion components ($\sin\theta$) have the same sign and thus cancel. The horizontal motion frequency shifts have opposite signs and are additive when the difference is taken.

$$v_x = (\Delta f_F - \Delta f_A)\left(\frac{c}{4f_s \cos\theta}\right) \tag{11}$$

Up/down velocity ($v_z$) is a function of the <u>sum</u> of the fore beam Doppler shift and the aft beam Doppler shift. In this case the horizontal motion frequency components ($\cos\theta$) have an opposite sign and thus cancel. The vertical motion frequency shifts have the same sign and are additive when the sum is taken.

$$v_z = (\Delta f_F + \Delta f_A)\left(-\frac{c}{4f_s \sin\theta}\right) \tag{12}$$

For a four-beam Doppler navigator, the port/starboard (p/s) shift is computed the same as the fore/aft shift except using the Doppler shift from the port/starboard pair. A Doppler navigator four-beam array is symmetrical with beams spaced 90 deg apart radially. A single-beam Doppler system of the configuration shown in Figure 28 is impractical because pitch and roll will introduce so much error. With a two- or four-beam JANUS configuration (Figure 29b) the effects of pitch and roll are considerably reduced. For instance, when a boat pitches bow down, the Doppler shift in the aft beam will be larger for a given horizontal velocity than is the case when the boat is not pitching. Under the same bow-down condition, shift in the fore beam will be smaller for a given horizontal velocity than is the case where the boat is not pitching. This pitch effect is very close to being equal in magnitude in the fore and aft beams. The difference between the Doppler shift in the fore and aft beams will therefore remain relatively unaffected by boat pitch. Since horizontal velocity is computed from the difference between the fore and aft beam Doppler shifts, the measured horizontal velocity will be affected very little by boat attitude when a boat uses a JANUS transducer assembly. Vertical motion has a short-term effect on measured horizontal velocity because the sine terms no longer cancel when the fore and aft angles are not equal. The vertical motion effect on horizontal velocity measurement is, however, averaged out over one

wave period because the up-going error is cancelled out by the down-going error. Since horizontal velocity is normally averaged over many wave periods, the pitch action has negligible effect on this measurement. Vertical velocity measurement using the JANUS configuration is somewhat more sensitive to pitch effects than is the horizontal velocity measurement. An increase in one beam's vertical motion Doppler shift is compensated by a decrease in the other beam's vertical motion Doppler shift. The horizontal motion induced Doppler shift in one beam is not fully compensated (on an instantaneous basis) by the other beam when the boat is pitching. The error in vertical velocity measurement due to horizontal boat velocity can be computed if pitch angle and horizontal velocity are measured.

## Dockside Experiments with Doppler Heave Unit

87. To validate the Doppler method of determining vertical boat motion, it was decided that field experiments were needed. Several manufacturers of Doppler speed logs and Doppler navigators were contacted regarding the possibility of converting a standard Doppler product into one with a vertical output. AMETEK/Straza appeared to offer the best package for the planned experimental purposes. An AMETEK/Straza Doppler speed log, model 4015, was therefore purchased. It had the normal horizontal Doppler velocity output signals and, in addition, signals that combined the sum of the fore/aft transducers. The signal processing in this unit thus takes the same transducer outputs and uses them two different ways. Processed in one way, the Doppler frequency shift gives a signal proportional to horizontal motion. Processed another way, the Doppler frequency shift gives a signal proportional to vertical motion. Both signals are available at the same time.

88. An initial test of the Doppler navigator heave unit was set up in 1980 as a dockside experiment so that conditions could be well controlled. The Doppler unit was installed in a hydrographic survey boat of the US Army Engineer District, Vicksburg, as shown in Figure 30. A large transducer well was added in the hull of the survey boat and the Doppler transducer assembly was mounted in this well. (The Doppler transducer assembly required a 10-in.-diam well whereas the depth transducer well was only 6 in. in diameter.) For the dockside tests, the transducer assembly was suspended by a test cable from an overhead pulley. The pulley support for the transducer assembly was

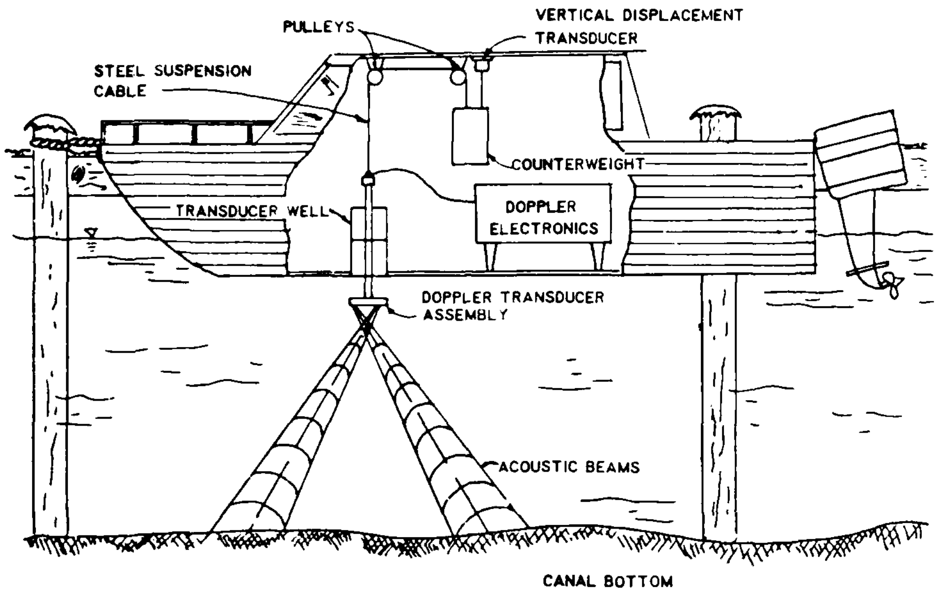



Figure 30. Doppler unit arrangement as installed in survey boat

counterweighted so that the assembly could be raised and lowered a distance of approximately 18 in. in a straight vertical line. With the counterweight, only a small force was needed to raise and lower the heavy transducer assembly. An electrical displacement transducer was attached to the pulley mechanism to directly measure the vertical motion of the Doppler transducer assembly. A simplified sketch showing the experimental arrangement for recording displacement is shown in Figure 31.

89. Signals proportional to the vertical velocity of the transducer assembly were generated in the Doppler electronics unit. Up/down signals were each in the form of a pulse rate that was directly proportional to vertical velocity. The AMETEK/Straza electronics unit provided "up" pulses at one terminal and "down" pulses at another terminal. Circuits were built at WES to integrate the up/down pulse rate so that vertical displacement could be computed from vertical velocity of the transducer assembly. The integration circuit built for the dockside experiments was an analog circuit. Frequency to voltage converters (F/V) changed each of the pulse rates for manipulation by an analog integrator. Output of the integrator was in the form of a voltage proportional to vertical displacement. The integrator included an adjustable feedback potentiometer that caused the integrator output to drift toward zero in the absence of an input signal. The circuit was adjusted so that output would return to zero in approximately 100 sec from an offset of approximately

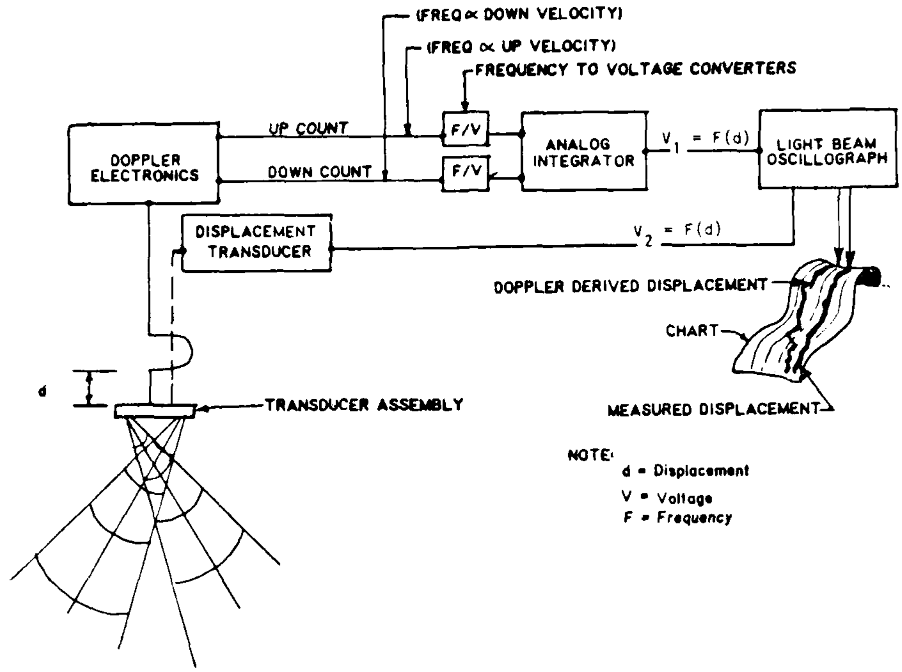



Figure 31. Experimental arrangement for recording displacement

10 percent of full scale. Without a "return to zero function," any real-world integrator will drift away from zero due to noise within the integrator itself or due to minor effects in the input signal. The return to zero function has a small attenuation effect on measured wave amplitude that is inversely proportional to frequency. Very low frequency components, such as tides, are completely filtered out. This return to zero function is similar to the 77-sec delayed integrator action in the HIPPY 120.

90. The output signal of the vertical velocity integrator was recorded in green on one channel of a two-channel strip chart recorder. The output signal of a displacement transducer was recorded in red on the other channel. The recorder pens were adjusted so that the center of the chart was zero for both. The integrator circuit gain and displacement circuit gain were both set so that 2 in. on the chart equaled 1 ft of vertical motion.

91. The Doppler transducer assembly was raised and lowered within the transducer well over a total range of approximately 18 in. Computed displacement (integrator) and measured displacement were recorded simultaneously on the recorder with the velocity of the vertical motion being changed for different runs. The motion was generated manually, and the experimenter

attempted to develop approximately a sinusoidal motion as observed on the recorder.

92. When a sinusoidal vertical motion pattern was generated with a period of approximately 10 sec, the two traces on the recorder followed each other very closely, indicating excellent agreement between Doppler-derived displacement and measured displacement. Agreement of better than 1 in. out of the 18-in. travel was typical for this case.

93. When a sinusoidal vertical motion pattern was generated with a period of approximately 100 sec, the Doppler-derived displacement was approximately 25 percent lower in amplitude than the measured displacement. This result was expected because of the built-in return to zero function. It was impractical to use longer time constants than 100 sec because intermittent false pulses from the Doppler unit would then cause the integrator to drift unacceptably. The 100-sec time constant was considered adequate for this phase of the development work.

94. When a sinusoidal vertical motion pattern was generated with a period of less than 5 sec, a second limitation was observed due to the transmitter pulse rate. The pulse rate of the standard AMETEK/Straza Doppler unit was set for approximately 1.6 pulses per sec, or 0.6 sec between pulses. The Doppler circuits in the electronics unit compute a velocity at the time a pulse returns and hold that value until the next pulse arrives. This causes the output pulse rate (velocity) to change in 0.6-sec steps. For short-period waves these steps are noticeable and give, in effect, a real-time lag equivalent to the period between pulses. After consultation with AMETEK/ Straza, WES personnel made modifications to the Doppler electronics that raised the pulse rate to 4 pulses per sec. This reduced the update time to 0.25 sec and improved the Doppler-derived displacement tracking for wave periods between 2 and 10 sec. Wave periods shorter than 2 sec are not considered significant for most Corps survey work as the boats themselves will largely attenuate high-frequency chop.

95. Results of these tests proved conclusively that the Doppler equipment would provide signals proportional to vertical velocity of the transducer assembly during dockside tests with calm water conditions and within the frequency range tested.

## River Operation on Survey Boat 8 (Vicksburg District)

96. Following the dockside tests in 1980, the Doppler transducer assembly was installed in the transducer well located in the hull of the survey boat. The face of the transducer assembly was positioned flush with the bottom of the hull of the survey boat, which is the normal mounting location for a Doppler navigator transducer. The transducer well cover was sealed to prevent water from splashing into the boat cabin under rough water conditions.

97. The survey boat was operated in the Mississippi River near Vicksburg, Mississippi, and the output of the Doppler unit was recorded with an oscillograph. Wave action in the Mississippi River was confined to relatively low amplitude chop which gave a little pitch and roll to the survey boat but little vertical motion. Observations of the recorded Doppler output indicated that the unit was functioning satisfactorily, but with only low-amplitude chop as a driving force it was not a conclusive test.

## Operation on Survey Boat *Hickson* (Portland District)

98. In order to try the Doppler unit under more realistic and significant wave conditions, it was decided that experiments on a coastal survey boat were now in order. In 1981, the Chief of the Survey Branch, US Army Engineer District, Portland, was contacted to see if that District would be interested in assisting with an experiment with the Doppler unit as a potential heave measuring device. They agreed, since the Portland District has a high percentage of its surveying work in waterways with significant wave action. The Portland District arranged to have a 10-in.-diam transducer well installed in the hull of the survey boat *Hickson*. The Doppler transducer well was located approximately 2 ft aft of the depth transducer well and near the center line of the hull. The Doppler electronics boxes were installed in the below-deck equipment compartment above the Doppler transducer well.

99. Following the installation of the Doppler unit by the Portland District, WES was notified when the *Hickson* was scheduled to run surveys in several small harbors along the Oregon coast. Significant wave action was expected in the inlets to be surveyed.

100. Two additional WES instruments were used during the survey trial runs. One was a gyro-stabilized accelerometer unit which was to be used as a

comparison check on the Doppler unit. The gyro-stabilized unit has two gyros within the case and three accelerometers. Signal outputs are pitch, roll, yaw, vertical acceleration, and two horizontal acceleration vectors. The gyro-stabilized accelerometer platform is shown in Figure 16. The second instrument was a magnetic tape recorder to record signals from the Doppler unit and the gyro-stabilized accelerometer. Pulses from one of the permanent depth sounders were also recorded. A block diagram showing the instruments used and the signals recorded is shown in Figure 32.

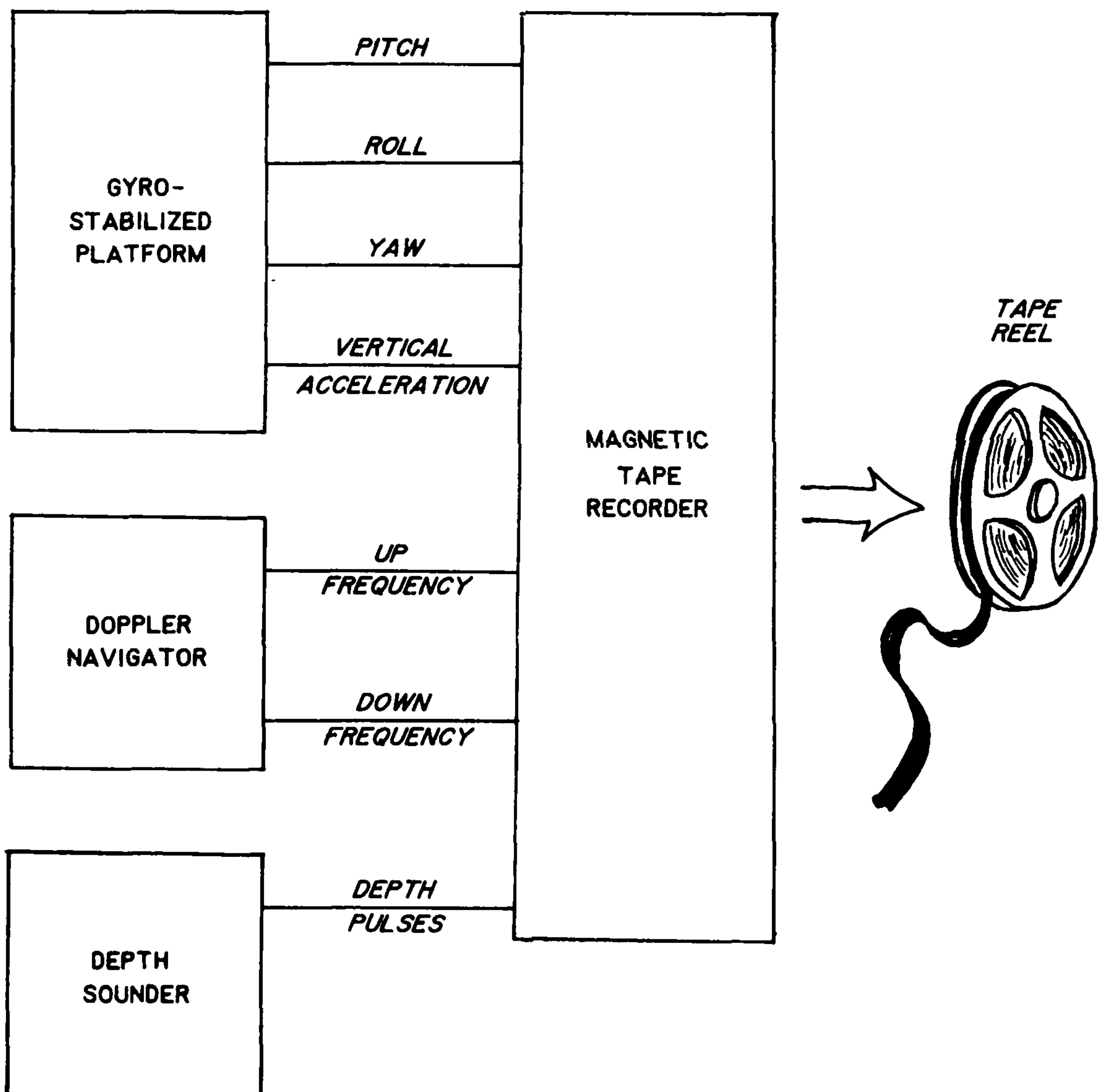



Figure 32. Block diagram of equipment used in Doppler field experiment

101. Magnetic tape recordings of Doppler signals and gyro platform signals were made during a coastal trip from Reedsport, Oregon, to Coos Bay, Oregon. Recordings were also made intermittently while the *Hickson* was making normal hydrographic surveys in the Coos Bay harbor inlet. The wave conditions were more than adequate for the intended purpose. During the coastal leg of the trip, the waves appeared to reach amplitudes of 12 to 15 ft. In the harbor inlet outside the jettys, the waves were 5 to 10 ft and coming in regular trains.

102. The Doppler unit did not experience any breakdown during the rough trip, and signals from it were recorded on magnetic tape at intervals during the coastal trip. The gyro-stabilized platform, however, developed problems early in the trip. The equipment experienced an unacceptable drift rate in the gyro and made the vertical accelerometer output signal useless for computing vertical displacement (using double integration). As a result of this equipment failure, it was impossible to correlate the vertical displacement measured using the Doppler unit with that from the gyro-stabilized platform unit. Visual observations of vertical displacement correlated with Doppler unit measurements as well as could be expected with the observer standing on a very unstable platform. This disappointing equipment problem on the first attempt with the Doppler system required that the necessary repairs be made and an additional trip planned.

103. Shortly after this first Doppler system field experiment was attempted, WES personnel learned that a Doppler heave compensation unit, manufactured by NAVITRONIC Corporation (Nielsen 1985), was soon to be commercially available. OCE was notified of this development in the commercial sector. Considering the disappointing shortage of funds available for continuation of this hydrographic survey research effort, OCE instructed WES to discontinue development of the Government-sponsored Doppler heave compensation system. It was felt that an effort to publish the available information contained herein and distribute it to the field elements involved with hydrographic survey efforts would be very beneficial. The reasoning for discontinuing the research was that the Government should not pursue an expensive development program when a product similar to the end result of the study and based on the same principle is commercially available. While there are some differences in the transducer arrangement and signal processing between the NAVITRONIC and the WES Doppler unit, the basic principle is identical. The NAVITRONIC unit

established the concept that Doppler shift could be used to determine, in a practical system, the vertical motion of a survey boat.

104. The NAVITRONIC Doppler heave unit must be used in conjunction with their depth measuring unit. The NAVITRONIC heave unit is thus not economical for retrofitting an otherwise complete system because the depth sounder would need to be replaced and the heave unit purchased. When selecting a completely new survey system for coastal surveys, the NAVITRONIC unit is recommended for consideration, if wave action is a significant factor.

105. There are currently no known US manufacturers of Doppler heave correction units. The inclusion of such a product in their line should be relatively easy for depth sounder and Doppler navigator manufacturers. The market obviously is not a large one and manufacturers are reluctant to invest in developing a product when they lack confidence that it will make money. From the sources of the products appearing on the market, European surveyors must have a higher incentive for improving survey accuracy than US surveyors. Surveyors who could use heave correction are encouraged to press their suppliers for improved products such as heave units. If US manufacturers can sense that the size of the potential market for more accurate depth sounders is growing, they will respond.

## PART V: CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

106. The following conclusions result from the analyses of the information and data gathered in this study.

a. Small errors in the vertical reference of hydrographic surveys can be very costly. Dredged material quantities and water/land boundaries are much more sensitive to errors in the vertical reference than to errors in the horizontal reference.

b. Surveyors too often assume that land is stable and that the water surface across a waterway is level and can be determined by a shore gage.

c. Satellites and subsurface instruments make it possible to check the static and slowly varying vertical reference with an accuracy and timeliness not possible a few years ago.

d. Heave corrections can best be computed by digital techniques that impose a lag on the real-time data. Heave correction can thus be done best during postsurvey plotting.

e. The HIPPY 120 should be a useful instrument for large survey boats working long survey lines.

f. At present there are no known US manufacturers of heave correction equipment for depth soundings. There are US manufacturers that produce equipment for correcting subbottom profile data for heave effects.

g. Doppler systems and laser displacement measuring systems have considerable promise for heave correction in the future.

h. The current state of the art is changing rapidly. Continued evaluation of new vertical motion measuring equipment is justified.

i. Survey vessel hull designs, other than conventional displacement, offer possibilities for considerably improved performance. Eliminating wave action effects is better than correcting depth data for wave action errors. Use of alternate hull designs will probably require the use of alternate surveying procedures, such as longitudinal survey lines rather than transverse survey lines.

### Recommendations

107. The following are recommended:

a. Districts should analyze the cost of survey inaccuracies on the project for which the survey is being made. Investment in

survey effort should be planned to minimize project cost, not just survey cost. A cheap survey can be very costly to the project as a whole.

b. All Districts should periodically reexamine the vertical shore references for hydrographic surveys, keeping in mind possible land uplift or subsidence and changing sea levels.

c. Keep vertical references updated with respect to the latest national grid standard and accepted definition of water level for navigation purposes.

d. Surveyors should use water level gages as close to the survey area as is technically possible and operationally practical.

e. Avoid data smoothing as much as possible. If heave compensation equipment is not available and wave action is severe, then make replicate passes over each section line to improve the statistical validity of the survey data.

f. Districts that must contend with heave problems in their surveys should consider trying one of the commercially available heave measuring systems. Heave compensation will add to the cost of making a survey but this cost is small compared with the indirect cost to the Government that will result from surveys that are less accurate than is practical with current technology. Applications that include small harbors with channel-to-shore distance less than 2,000 ft may be able to use an optical system like the Laserplane. Applications in major bays and coastal waters may be able to use systems like the NAVITRONIC HTC-1 (Doppler) or the Atlas Heco 10 (inertial).

g. Software should be a major consideration when selecting a heave compensation system. Changing the software of an existing system to incorporate the heave correction functions will involve an extensive rewrite. This will be time-consuming and expensive. A supplier that can provide both software and hardware may be able to offer the most cost-effective solution. If one company is responsible for supplying the complete system, including the heave components, then there can be no argument about responsibility for making the system work.

h. Districts wishing to add heave compensation to an existing survey system may find the upgrade simpler if heave data are recorded on a separate recorder using a common time lag on the heave data and the position data. Heave correction can be performed during postsurvey processing of the data.

i. Survey boat design can have a big impact on the ability of a District to conduct accurate and safe surveys under given wave conditions. Further investigation of alternate survey vessel hull designs is recommended.

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# APPENDIX A: SURVEY EQUIPMENT SUPPLIERS

| Company | Product/Service |
|---|---|
| Abema, Inc.<br>10 Fitch Street, PO Box 775<br>Norwalk, Connecticut 06856 | Topographic Survey Supplies |
| Allied Surveyor Supplies Mfg.<br>3225 East 47th Street<br>PO Box 27367<br>Tucson, Arizona 85726 | Survey Monuments |
| Alpha Electronics<br>8185 South Grant Way, PO Box 2073<br>Littleton, Colorado 80122 | Distance Measuring Equipment |
| AMETEK/Straza Division<br>770 Greenfield Drive<br>PO Box 666<br>El Cajon, California 92022 | Doppler Navigators |
| Autometric<br>5205 Leesburg Pike<br>Suite 1308, Skyline 1<br>Falls Church, Virginia 22041 | Topographic Survey Suppliers |
| Bartex, Inc.<br>PO Box 3348<br>Annapolis, Maryland 21403 | Tide Gage and Telemetry |
| Bernsten Cast Products<br>100 East Broadway<br>Madison, Wisconsin 53704 | Survey Monuments |
| Cubic Precision Corporation<br>5650 Kearny Mesa Drive<br>PO Box 85587<br>San Diego, California 91238 | Distance Measuring Equipment |
| Data-Sonics<br>PO Box A61<br>North Falmouth, Massachusetts 02556 | Distance Measuring Equipment |
| Datawell B. V.<br>Zommerlust Straat, 4<br>Haarlem, The Netherlands | Heave Compensation Equipment |
| Del Norte Technology<br>PO Box 696<br>Euless, Texas 76039 | Distance Measuring Equipment |

| Company | Product/Service |
|---|---|
| Digital Design & Development<br>Industrial Park<br>PO Box 225<br>Hingham, Massachusetts 02043 | Custom Microcomputer Systems |
| Earl Dudley & Associates<br>5352 First Avenue, North<br>Birmingham, Alabama 35212 | Topographic Survey<br>Equipment Sales, Rentals, Repairs |
| Edo Western<br>2645 South Second Street<br>Salt Lake City, Utah 84115 | Subbottom Profilers<br>Doppler Navigations |
| EG&G<br>151 Bear Hill Road<br>Waltham, Massachusetts 02159 | Subbottom Profilers<br>Side Scan Sonar |
| ENDECO<br>Tower Building<br>Marion, Massachusetts 02938 | Environmental Measuring Equipment |
| Engineering Services Associates<br>1500 Massachusetts<br>Washington, DC 20005 | Survey Equipment |
| GEO/HYDRO, Inc.<br>2115 East Jefferson Street<br>Rockville, Maryland 20852 | Global Positioning System Equipment |
| GTE Sylvania<br>PO Box 188<br>Mountain View, California 94040 | Electrooptical Tracking Systems |
| Harvey-Lynch, Inc.<br>10669 Richmond<br>Houston, Texas 77042 | Magnetometers |
| Hewlett Packard<br>PO Box 301<br>Loveland, Colorado 80537 | Optical Distance Measuring Equipment<br>Total Surveying Station<br>Data Acquisition Systems<br>Data Processing Systems |
| Innerspace Technology, Inc.<br>One Bohnert Place<br>Waldwick, New Jersey 07963 | Depth Digitizers<br>Depth Recorders |

| Company | Product/Service |
|---|---|
| International Technology, Ltd.<br>(Itech)<br>9000 Clay Rd.<br>Suite 110, Pineway Business Court<br>Houston, Texas 77040 | Contract Inertial Surveys |
| Kern Instruments, Inc.<br>Geneva Road<br>Brewster, New York 10509 | Topographic Survey<br>Equipment Field Instruments |
| Keuffel & Esser Company<br>20 Whippany Road<br>Morristown, New Jersey 07960 | Topographic Survey Equipment<br>Field Survey Systems<br>Office Computer Survey Systems |
| Klein Associates, Inc.<br>Klein Drive<br>Salem, New Hampshire 03079 | Side Scan Sonar |
| Krupp Atlas Elektronik<br>241 Erie Street<br>Jersey City, New Hampshire 07302 | Depth Sounders<br>Distance Measuring Equipment<br>Computerized Survey Systems<br>Sweep Systems |
| The Lietz Company<br>9111 Barton Street, Box 2934<br>Overland Park, Kansas 66201 | Topographic Survey Equipment |
| Mitchell Marine<br>PO Box 90340<br>Lafayette, Louisiana 70509 | Survey Boats |
| MonArk Boat Company<br>PO Box 210<br>Monticello, Oklahoma 71635 | Survey Boats |
| Motorola, Inc.<br>Government Electronics Division<br>Mail Drop T<br>South Price Road<br>Tempe, Arizona 85282 | Distance Measuring Equipment<br>Complete Survey Systems |
| NAVITRONIC<br>Marselis Boulevard<br>DK-8000 Aarhus C<br>Denmark | Depth Sounders<br>Sweep Systems<br>Computerized Survey Systems |

| Company | Product/Service |
|---|---|
| Nicolet Zeta<br>101 Governor's Drive<br>Suite 504, Bank of Huntsville<br>Building<br>Huntsville, Alabama 35810 | Plotters |
| Ocean Research Equipment<br>PO Box 709<br>Falmouth, Massachusetts 02541 | Subbottom Profilers<br>Side Scan Sonar |
| Odom Offshore Surveys<br>PO Box 927<br>Baton Rouge, Louisiana 70821 | Contract Surveys<br>Survey Systems<br>Depth Sounders<br>Distance Measuring Equipment<br>Range Azimuth Systems |
| RACAL - Decca Survey, Inc.<br>10401 Westoffice Drive<br>Houston, Texas 77042 | Contract Surveys<br>Complete Survey Systems |
| Raytheon Ocean Systems Company<br>10 Risho Avenue<br>Westminister Park<br>East Providence, Rhode Island 02914 | Depth Measuring Equipment<br>Contract Surveys |
| Ross Laboratories, Inc.<br>3138 Fairview Avenue, East<br>Seattle, Washington 98102 | Depth Measuring Equipment<br>Sweep Systems |
| Sanders Corporation<br>Nashua, New Hampshire 03061 | Electrooptical Tracking<br>Systems |
| Schonstedt Instrument Company<br>1775 Wiehle Avenue<br>Reston, Virginia 22091 | Magnetometers |
| SEACO, Inc.<br>2560 Huntington Avenue<br>Alexandria, Virginia 22303 | SWATH Boats |
| Sea Systems Corporation<br>PO Box 1042<br>Deerfield Beach, Florida 33441 | Surveying Equipment |
| Spann International<br>7330 Shoeman Lane<br>Scottsdale, Arizona 85251 | Contract Inertial Surveys |

| Company | Product/Service |
|---|---|
| Spectra-Physics<br>5475 Kellenburger Road<br>Dayton, Ohio 45424-1009 | Laserplane Laser Leveling Instruments |
| Teledyne/Radist<br>PO Box 1275<br>Hampton, Virginia 23361 | Distance Measuring Equipment |
| Teludist<br>PO Box Y<br>Mastic, New York 11951 | Distance Measuring Equipment |
| The Carl Zeiss Company<br>PO Box 378<br>Donald, Oregon 97020 | Topographic Survey Equipment<br>Field Instruments<br>Survey Data Processing Equipment |
| Topcon Instruments<br>1090 McConnell Drive<br>Decatur, Georgia 30033 | Land Surveying Equipment |
| Universal Technology, Inc.<br>OPTRON Division<br>30 Hazel Terrace<br>Woodbridge, Connecticut 06525 | Video Optical Tracking System |
| Wild Heerbrugg Instruments, Inc.<br>465 Smith Street<br>Farmingdale, New York 11735 | Topographic Survey Equipment |
| Wimpol, Inc.<br>PO Box 219218<br>Houston, Texas 77218 | Survey Systems |

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